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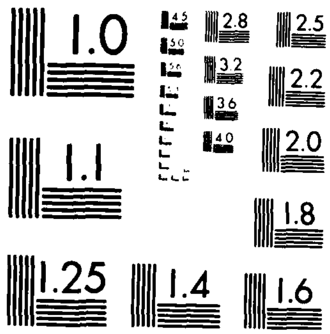

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ENERGY CONSIDERATIONS IN SECOND BREAKDOWN

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February 1985

Final Report

Approved for public release; distribution unlimited.

AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117-6008

AFWL-TR-84-111

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This technical report has been reviewed and is approved for publication.

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The energy between the beginning of turn-off and the onset of second breakdown, dissipated at the collectors of power transistors switching inductive loads, was determined and plotted vs the time to second breakdown. A linear relationship was obtained, excluding a thermal initiation mechanism, which requires a $t^{1/2}$ dependence.

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I. INTRODUCTION

This work was conducted to investigate the properties of junction switching transistors as they are driven into second breakdown. Second breakdown is an instability that occurs when a transistor is subjected to simultaneous high collector voltages and currents, such as those that may be induced in the presence of an electromagnetic pulse. An understanding of the physical mechanisms which lead to second breakdown is essential for the prediction of circuit failure in such an environment. Reverse bias second breakdown, which is particularly severe because of the high power which may be dissipated in the device, occurs when the load is inductive and is initiated when a transistor is being turned off. It is characterized by a rapid fall in collector-emitter voltage, accompanied by an increase in collector current, and generally results in destruction or degradation of the device. However, a nondestructive measurement technique has been developed (Ref. 1) in which the transistor is protected by way of a collector current crowbar which triggers when the instability has been detected. Such a system was constructed and used at Texas Tech University previously (Ref. 2). The present work, which is based on these earlier results, had a two-fold objective: to investigate in more detail the possible exclusion of a thermal initiation mechanism, and to extend the measurement to lower temperatures. It had two subsidiary objectives as well: to establish the limitations of the measurements which depend on the test system itself, and to develop a system for the rapid acquisition and processing of large quantities of data.

II. EXPERIMENTAL PROCEDURES

GENERAL DESCRIPTION OF THE TESTER

The test system was described in detail in Reference 2, but a review of its operation will be useful here. The transistor under test (TUT) is turned on initially with a base current pulse generated by the forward pulse generator (Figure 1); the amplitude of this pulse is controlled by the variable gain current amplifier, and its duration by the timing section. The load is a 1 mH inductor, linear to about 30 A. The collector supply is a variable current limited voltage source which is gated on and off by the timing circuit of the base drive. The initial state of the TUT is controlled by varying the forward pulse amplitude, the pulse duration, or the collector supply voltage. Immediately following the forward base pulse, the timing circuit triggers the reverse pulse generator, which drives a second variable gain current amplifier. After the charge stored in the base region has been removed by the reverse base current, the collector current begins to fall; the collector-emitter voltage increases because of the energy stored in the magnetic field of the inductor. At some point during transistor turn-off, an instability generally occurs, and the collector-emitter voltage falls rapidly, typically 500 V in 25 ns. The rapid transition causes a displacement current in the detection capacitor, triggering the high

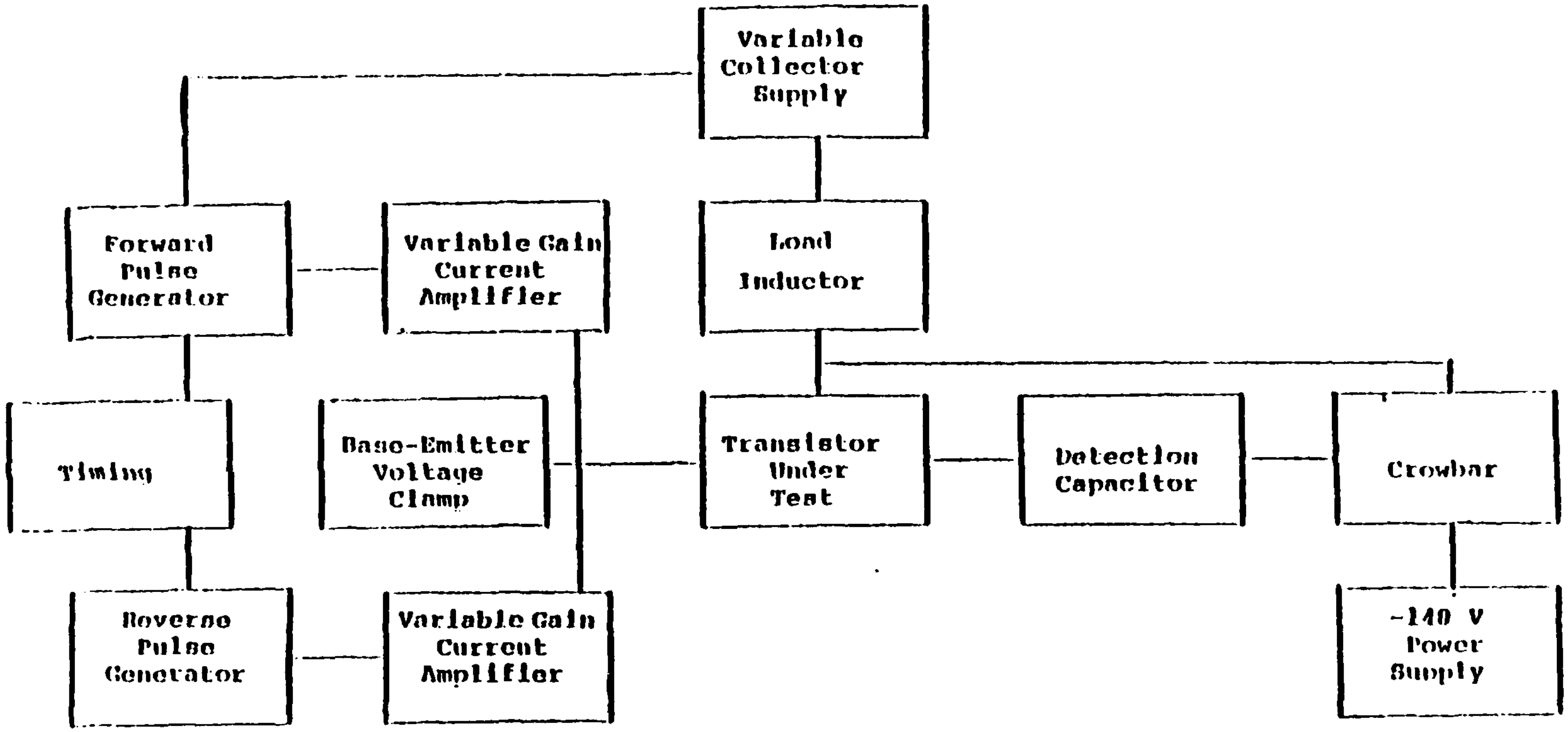


Figure 1. Block diagram of the tester.

speed crowbar. The collector current is then diverted through the crowbar to the -140 V power supply. Clamp supplies limit the base emitter and collector-emitter voltages (the collector-emitter clamp is not shown).

MEASUREMENT APPARATUS

Waveforms were recorded on a Tektronix 7834 400 MHz storage oscilloscope, using 7A19 single-trace 600 MHz vertical amplifiers. Two time bases, the 7B80 and 7B85, provided the sweep. The collector-emitter voltage was measured with a Tektronix P6057 100X probe having a 1.4 GHz bandwidth, and the base-emitter voltage, with a Tektronix P6056, 10X, 3.5 GHz probe. Base and collector currents were measured with Pearson Model 411 current transformers, with rise times of 10 ns and outputs of 50 mV per A.

COLD FINGER AND DEVICE FIXTURE

A copper cold finger was constructed to permit low temperature cooling. The cold finger was made from a 3/8 inch diameter copper rod bent into the form of a J. A flat section was milled on the short end and a hole was drilled to permit the cold finger to be bolted directly to the TUT. A small circular disk, 1-1/2 inches in diameter, was welded onto the long end of the cold finger; this increased surface area immersed in the coolant, in this case, liquid nitrogen. As much of the cold finger as was practical was previous work (Ref. 2), although still in a nearly logarithmic sequence, were not exactly at the values specified, particularly at high currents. (For some of the measurements at low temperatures in this work, , the reverse base drive could not supply more than 2 A to the transistor. It is not clear what caused the limitation.)

TRANSITION TIME

The transition times between the forward and reverse base pulses varied with the pulse amplitude, from around 100 ns at equal forward and reverse base drives of 50 mA to some 2 μs at equal base drives of 11 A; Figure 9 illustrates the latter transition. (Transition time measurements were made with a current transformer on a transistor with the collector open circuited.) This is an important limitation of the tester, because at high reverse base currents the transistor may go into second breakdown before the reverse base current reaches its final value. Various attempts were made to improve the transition time, but these yielded only minor improvements. This problem had been recognized previously (Ref. 3), but it had been assumed that the turn-off delay time was long enough so that the reverse base drive would reach its final value before second breakdown. This assumption was found to be invalid for much of the present work, and additional work will require redesign of the drive circuits.

IV. EXPERIMENTAL RESULTS

TEST CONDITIONS

The voltage set at the collector supply was arbitrarily chosen to be 10 V. The emitter base voltage was clamped at 6.5 V and the collector-emitter voltage was left unclamped. The forward and reverse pulse widths were set to 4.5 and 10 ms, respectively. The former is long enough to establish the initial state of the transistor, but short enough to prevent saturation of the collector current transformer. Measurements were made at room temperature, approximately 20 to 25 °C, and at low temperatures between -30 and -60 °C. The forward base current pulse amplitude was held constant at some value, while the reverse base current pulse amplitude was varied in the approximately logarithmic sequence 0.05, 0.1, 0.2, 0.5, 1, 2, 5 and 11 A. At first, as in the previous work (Ref. 2), the current levels were obtained by setting calibrated controls on the front panel. These controls were calibrated by inserting a 1 Ω resistor in the base-emitter terminals on the test fixture and measuring the voltage drop across the resistor. Later experimentation revealed that the base drive was load dependent, so the calibrated control scheme was abandoned in favor of using a current transformer with a fast rise time and low percentage droop to insure that the base currents were at the specified values. Hence, the current levels in the

The value for instantaneous
Vce at the final point is
683 V at 6.04 us.

The value for instantaneous
Ic at the final point is
.781 A at 6.04 us.

The value for instantaneous
POWER at the final point is
534 W at 6.04 us.

The value for instantaneous
ENERGY at the final point
is 5870 uJ at 6.04 us.

The time at 10%
of the second-breakdown voltage
is To=.622 us.

The value of instantaneous
Vce at To is 68.3 V.

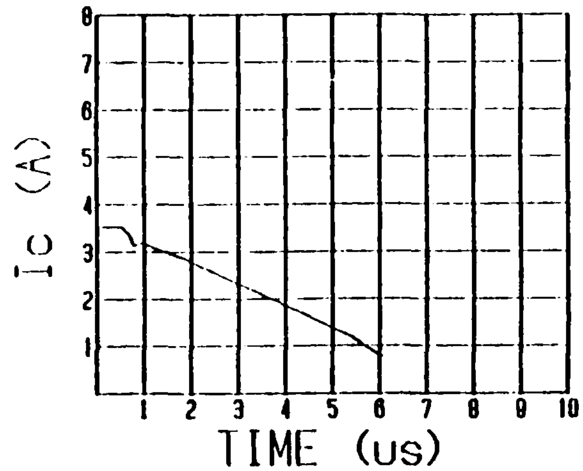
The value of instantaneous
Ic at To is 3.42 A.

The value of instantaneous
ENERGY
at To is 47.3 uJ.

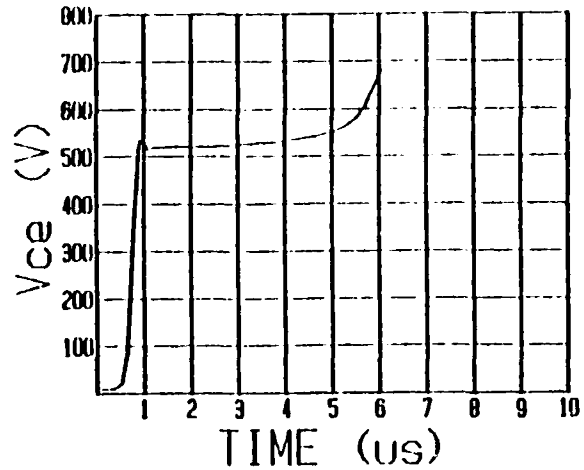
The change in ENERGY from
To to second-breakdown is
5820 uJ.

To to second-breakdown is
5.42 us.

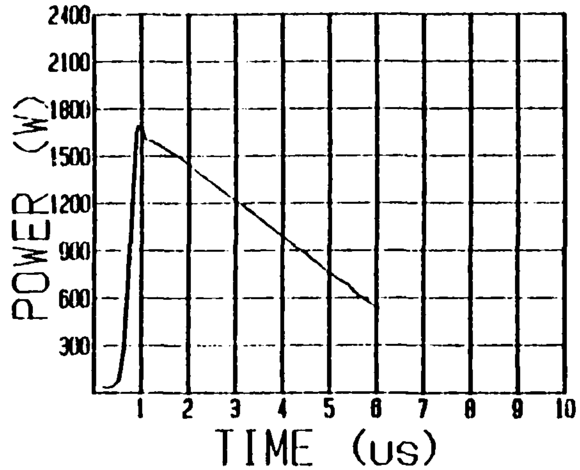
Figure 8. Data printout.



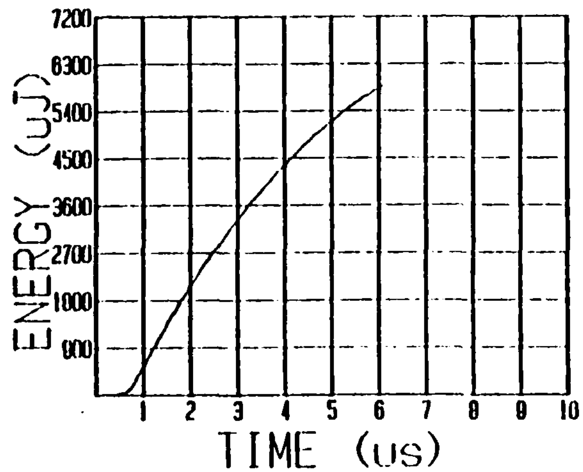
(a) Collector current vs. time



(b) Collector-emitter voltage vs. time



(c) Instantaneous power vs. time



(d) Energy vs. time

Figure 7. Collector current, collector-emitter voltage, instantaneous power, and energy vs. time.

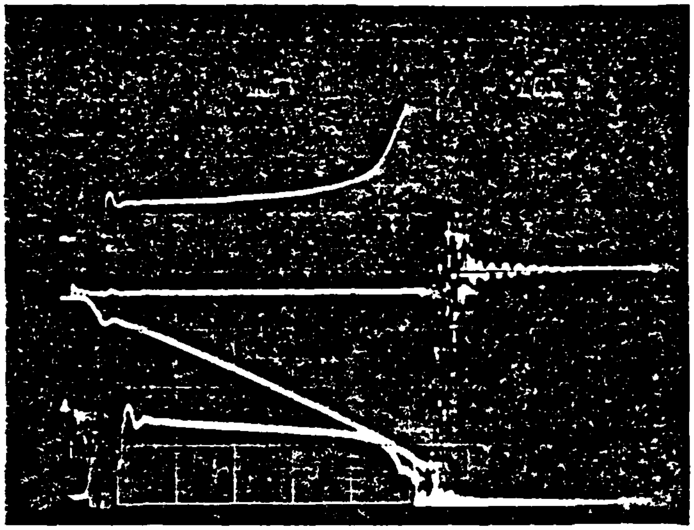


Figure 6. Collector-emitter voltage (uppermost waveform), collector current (triangular waveform) and base-emitter voltage (lowest waveform) as functions of time.

emitter voltage, collector current, instantaneous collector power, and energy at the final point was outputted. Finally, the total energy, E_{SB}, dissipated at the collector between T_o and second breakdown, and the difference between T_o and the final point, that is, the time to second breakdown, t_{SB}, were calculated and printed. Figures 6, 7 and 8 illustrate the operation of the programs. Figure 6 is a photograph of representative waveforms, Figure 7 illustrates the various curves obtained from the program, and Figure 8 shows the data printout corresponding to the curves. The scale factors can be adjusted to change the dimensions of the plots; also a plot of time dependent variables against each other (collector current vs. collector emitter voltage) can be obtained.

graphics tablet and the points representing the exterior corners of the photographic coordinates were manually digitized and fed to the computer. The degree of rotation, if any, of the coordinates relative to the graphics tablet was calculated, then used to rotate all subsequent data as required. Remaining data, consisting of waveforms, were digitized manually. The rotated data were stored in an internal register until data entry was complete and the program was instructed to store the data on floppy disk. The data were stored in an x-y format for later calculations. A plot of the stored data, and a printout of important device data (manufacturer, type, fabrication), device number, test conditions, and summary results were provided.

After two designated waveforms (relative to the same time scale) had been entered, additional points were calculated by interpolation, and a product curve was obtained. Here, collector current and collector-emitter voltage were entered *vs*. time, and instantaneous power was calculated. The time integral of the power curve was then obtained to provide the energy dissipated at the collector as a function of time. The calculation also provides the time, T_o, at which the principal input curve (collector-emitter voltage) is at 10% of its peak value; collector-emitter voltage, collector current, and energy at this time were then outputted. Time at second breakdown (discontinuous fall in collector-emitter voltage) was obtained, and collector-

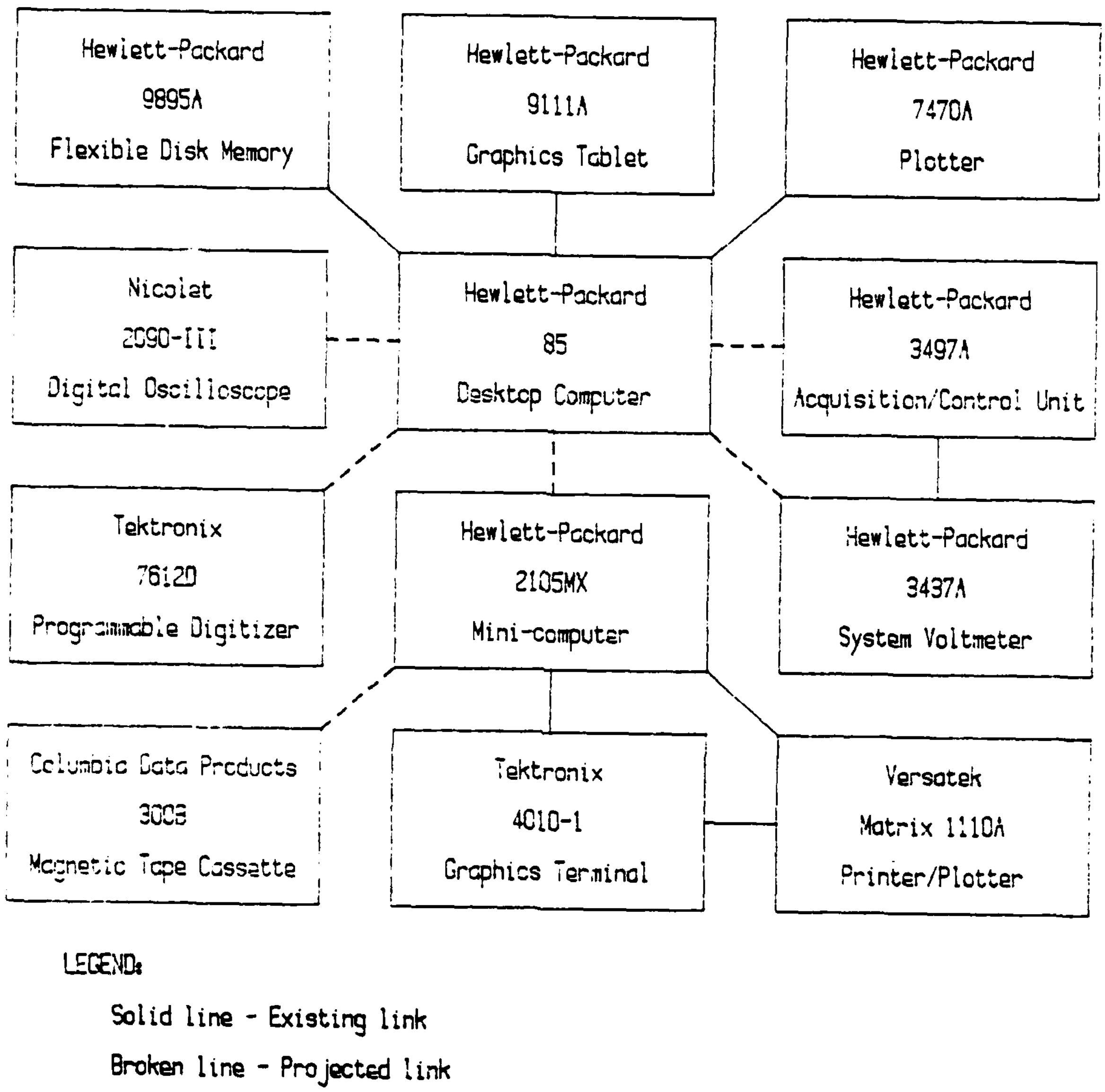


Figure 5. Data entry and analysis system.

III. DATA ENTRY AND ANALYSIS

The planned system for acquiring fast transient data rapidly from large numbers of devices, and for storage and analysis of these data, is shown in Figure 5. The system controller is an HP-85 desktop computer which interfaces with an HP-2105 microcomputer. The microcomputer buffers a graphics terminal, a printer-plotter, and a magnetic tape mass storage unit. The HP-85 itself connects to a multiplexer and digital voltmeter, a digital oscilloscope, a transient digitizer, graphics tablet, disc storage unit, and printer-plotter. The three instrument groups (HP-3497A and 3437A, Nicolet 2090-III, and Tektronix 7612D) represent a capability for sampling rates varying between several hours (HP-3497A and 3437A) and 5 ns (Tektronix 7612D). Because of its complexity, it was not possible to complete the assembly of the entire system during the contract period; existing and projected links are shown in Figure 5.

It was not possible to deliver data directly from the test system to the HP-85 *via* the Tektronix 7612D. However, although intermediate data storage on film was required, parts of the system could be used for entry and analysis of large quantities of data. Two separate processes were required: data entry using the program MASTER, and calculations with the program MATHPK. (These programs are listed in Appendixes A and B.) A photograph was affixed to the

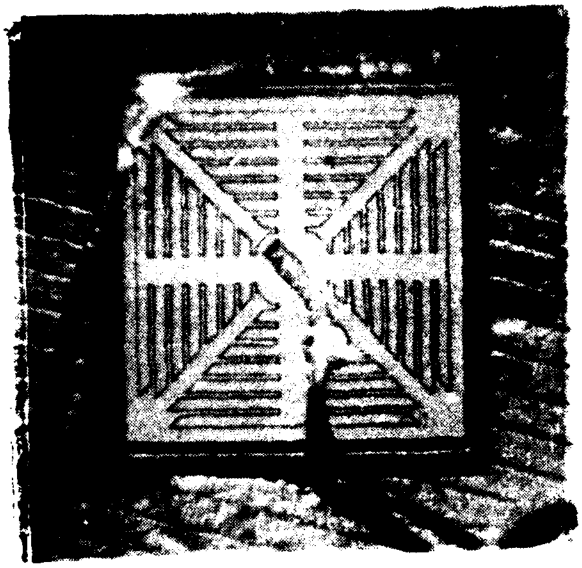


Figure 4. NH mask pattern (9X magnification.

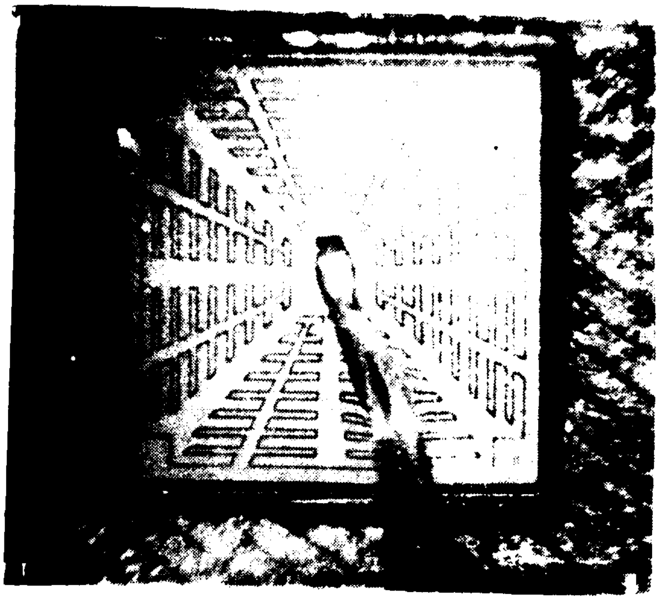
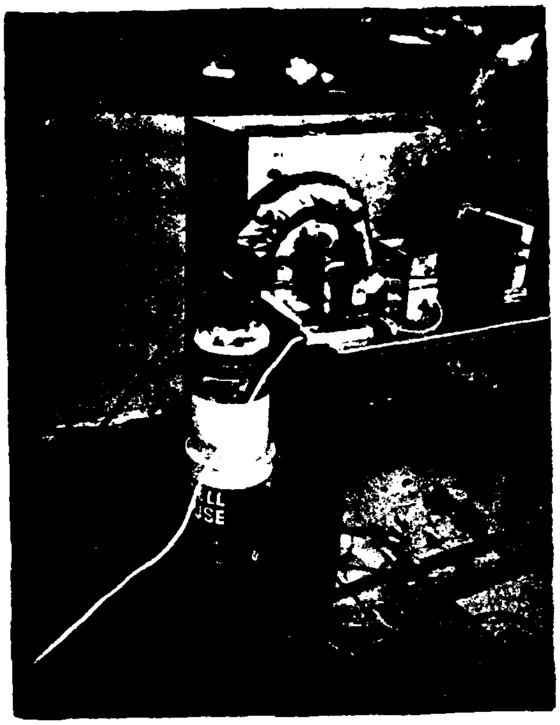


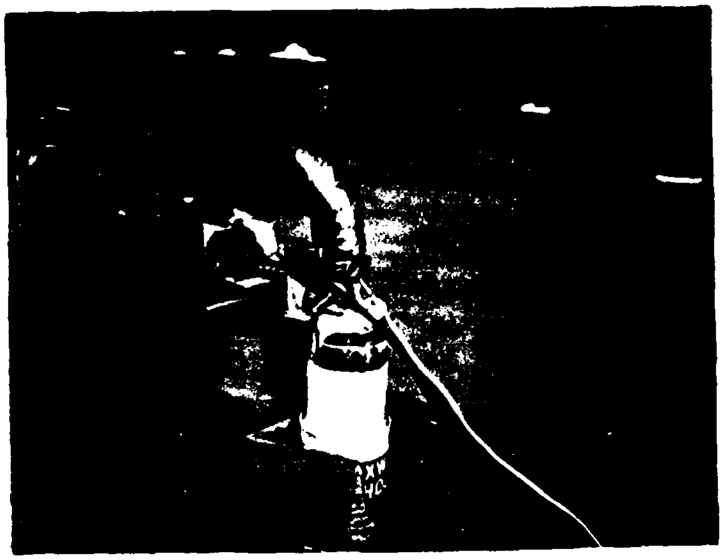
Figure 3. NE mask pattern (9X magnification.

only a limited number of devices were used. Since most of the previous data (Ref. 2) were obtained with Unitrode prototype devices similar to the BUX 98 (30 A, 400 V), samples of these transistors were also used here, two from one lot (NE) and two from a second lot (NH). Devices 19 and 36 are from lot NE-18W, and devices 26 and 37 are from lot NH-220-5.

The difference in the two lots is the emitter design; Figure 3 is a photograph of the NE structure, and Figure 4 shows the NH pattern. The devices are double-diffused single die structures, with an n^+-epitaxial substrate. Base sheet resistance is around 700 Ω/□ under the emitter stripe and around 60 Ω/□ between emitter fingers. The NE die has an area of 0.32 cm^2, the NH die, 0.22 cm^2.



(a) Front view



(b) Rear view

Figure 2. Cold finger and device fixture.

wrapped in insulated foam and duct tape to minimize thermal losses. The device fixture, a section of printed circuit board for the minimization of strays, was coated with a silicone encapsulant and a sprayed foam insulator to prevent thermal losses and inhibit ice buildup. The cold finger and device fixture are shown in Figure 2. However, even with insulation, it was not possible to reduce the temperature of the test device to below around -60 °C. There was not sufficient time during the course of this work to design and construct a low stray inductance and capacitance fixture which would permit measurements at lower temperatures.

A Type K thermocouple was constructed from 20 gauge chromel and alumel wires; the bead was inserted into a small hole drilled into the base of the transistor package adjacent to the die. The thermocouple was held in place with Epo-Tek H70E, a thermally conductive and electrically insulating epoxy adhesive. The thermocouple leads were connected to an Omega miniature cold junction for Type K thermocouples. The output was measured with a Keithley Model 177 digital multimeter. The measured voltages were converted to temperature using standard tables; accuracy is estimated at $\pm$ 1/2 °C.

TEST DEVICES

Because of the extensive measurements which were performed to assure characterization over all operating ranges,

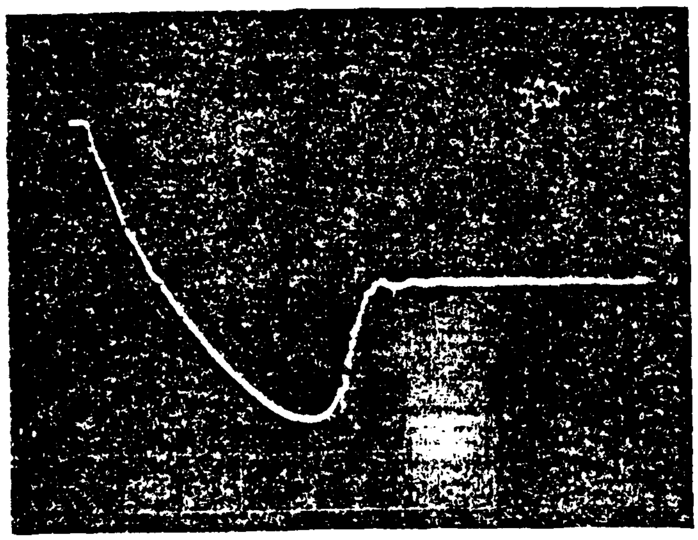


Figure 9. Transition between an 11 A forward and an 11 A reverse base pulse.

TYPES OF SECOND BREAKDOWN

In general, the same types of second breakdown observed in the previous work (Ref. 2) were also observed here. These were designated as Types A, B and C; their descriptions are repeated here for convenience.

Type A (Figure 10) -- The transistor was initially in the normal active region or just quasisaturated. This type of breakdown was normally observed when both forward and reverse base pulse amplitudes were small. Following a delay time, the collector emitter voltage rapidly increased to the sustaining voltage, $V_{CEX(SUS)}$, and remained there for several microseconds before increasing to the second breakdown voltage. The base-emitter voltage remained positive during the delay time and the sustaining period, but it decreased as V_{CE} increased, approaching zero as V_{CE} continued to rise. For Type A breakdown, t_{SB} was long enough to allow the reverse base current to reach its final value. The collector current decreased linearly to a value much less than its maximum at turn-off. Large amounts of energy, of the order of several thousand microjoules, were delivered to the collector during Type A breakdown.

Type B (Figure 11) -- The transistor was normally in quasisaturation prior to turn-off. V_{CE} reached $V_{CEX(SUS)}$ and remained constant until second breakdown. The base-

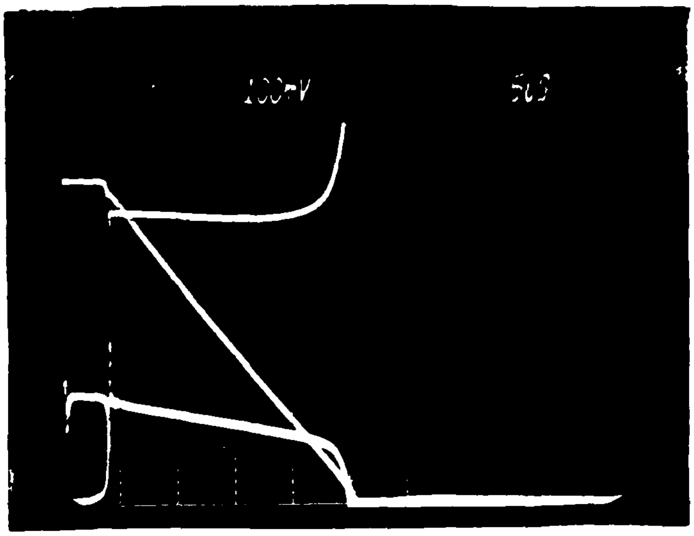


Figure 10. Typical Type A waveforms. The top curve is V_{CEX} (100 V per large division), the middle curve is I_C (2 A per large division), and the lowest curve is the base-emitter voltage during reverse base current, V_{BER} (o.5 V per large division).

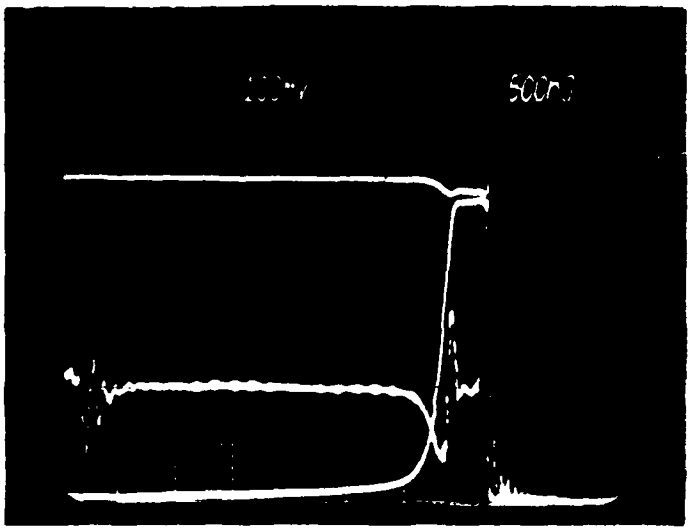


Figure 11. Typical Type B waveforms. The top curve is I_C (2 A per large division), the center curve is V_{BER} (0.5 V per large division), and the lowest curve is V_{CEX} (100 V per large division).

emitter voltage remained positive prior to second breakdown, and the base current generally had time to reach its final value. The collector current did not decrease appreciably during turnoff. The energy delivered to the collector during Type B breakdown was also on the order of a few thousand microjoules. Type B was found to be relatively uncommon.

Type C (Figure 12) -- Type C breakdown was observed for all high forward base currents, and for low forward base drives with high reverse base currents. The collector-emitter voltage did not reach its sustaining value and the collector current did not decrease appreciably. The base-emitter voltage became negative before second breakdown. The energy delivered to the collector during Type C second breakdown varied from a few thousand microjoules to less than a hundred; however, the instantaneous power at the collector at second breakdown was generally larger than for Types A or B.

To test reproducibility, the measurements made in the previous work (Ref. 2) were repeated. A minor change in the base drive circuit (Figure 13) made it possible to increase the forward base drive, so that the device could be driven harder toward initial saturation. Only Type C breakdown was observed with the higher forward base drive regardless of

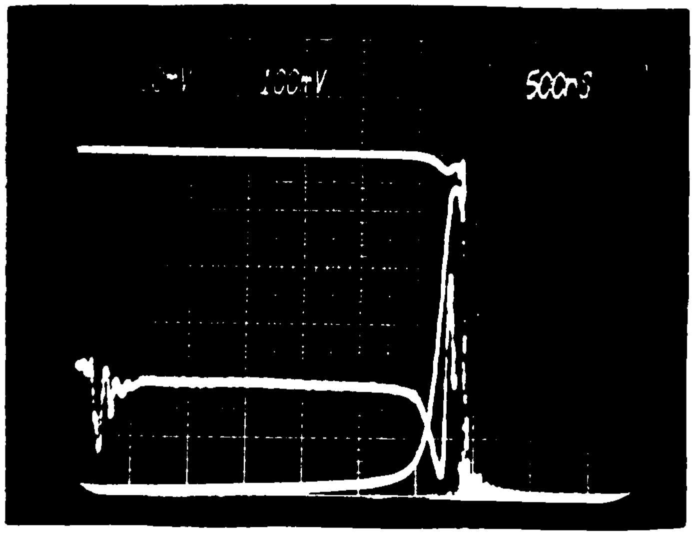


Figure 12. Typical Type C waveforms. The top curve is I_C (2 A per large division), the center curve is V_{BER} (0.5 V per large division), and the lowest curve is V_{CEX} (100 V per large division).

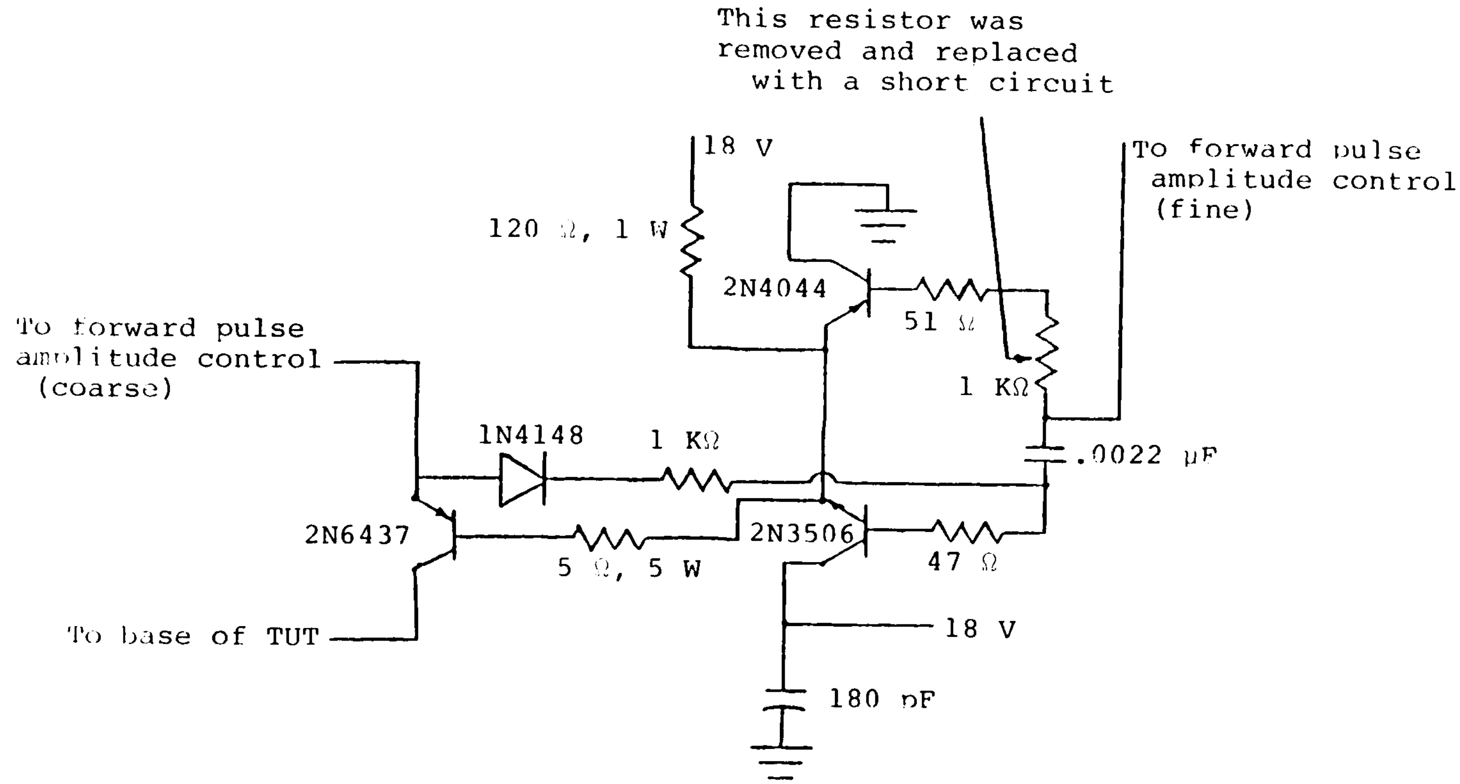


Figure 13. Base drive circuit modification for higher forward base drive.

the amplitude of the reverse base current pulse.

LOW TEMPERATURE MEASUREMENTS

It is interesting to compare the low temperature results with those made at room temperature. In general (although not always), the collector-emitter voltages at second breakdown, V_{SB}, were lower than those obtained at room temperature. Both the delay time, t_d, and the time to second breakdown, t_{SB}, decreased at the lower temperature, and breakdown shifted from the slower types to the more rapid types; i.e., under the same base drive conditions, a device which exhibited Type A breakdown at room temperature displayed Type B or C at a low temperature, and a device with Type B at room temperature shifted to Type C at a low temperature. Table 1 contains representative data comparing the behavior of a device (Number 19) at room temperature and at low temperature. Also, the devices appeared to be more vulnerable at lower temperatures, degrading considerably with repeated measurement. This degradation was manifested as a rapid increase in the collector-emitter voltage during turnoff, sometimes as great as 400 V in 10 ns. This was not a reproducible phenomenon. As the test continued, one of the devices would not sustain a large collector-emitter voltage during turnoff, and V_{CE} rose to only 10 to 15 V. A faster crowbar or reduced clamp voltages may be required to study second breakdown at low temperatures.

Table 1.

COMPARISON OF ROOM TEMPERATURE AND LOW TEMPERATURE BEHAVIOR FOR DEVICE NUMBER 19

Note: I_{BF} (forward base drive), I_{BR} (reverse base drive), and I_{CSB} (collector current at second breakdown) are in amperes; V_{SB} (collector-emitter voltage at second breakdown) is in volts; and t_{SB} (time to second breakdown) is in microseconds.

$I_{BF} = 0.05$

	T = 25 °C				T = -44 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	560	1.0	7.0	A	540	0.8	2.8	A
0.10	537	2.2	3.5	A	540	1.2	1.6	A
0.20	574	2.0	0.80	A	560	1.5	0.60	A
0.50	635	3.2	0.20	A	625	1.2	0.22	C
1.0	667	2.1	0.20	C	710	1.2	0.24	C
2.0	720	2.6	0.10	C	740	1.2	0.30	C
5.0	761	4.0	0.09	C	740	1.2	0.30	C
11.0	790	2.8	0.06	C	740	1.2	0.27	C

$I_{BF} = 0.10$

	T = 25 °C				T = -44 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	560	1.0	11.7	A	550	-	8.3	A
0.10	554	4.1	4.8	A	520	1.5	5.5	A
0.20	550	5.8	0.56	A	520	3.7	0.91	A
0.50	597	4.4	0.21	C	540	3.6	0.15	C
1.0	648	4.6	0.11	C	700	3.2	0.15	C
2.0	686	4.4	0.09	C	750	3.0	0.15	C
5.0	779	3.3	0.06	C	700	3.2	0.12	C
11.0	752	4.5	0.05	C	750	3.5	0.15	C

$I_{BF} = 0.20$

	T = 25 °C				T = -55 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	574	1.2	15.1	A	420	-	4.3	B
0.10	548	4.4	7.8	A	420	6.0	3.8	B
0.20	512	7.7	0.46	C	500	6.0	3.8	B
0.50	552	7.5	0.17	C	480	7.0	0.15	C
1.0	606	6.8	0.16	C	600	6.0	0.10	C
2.0	641	6.3	0.07	C	620	6.0	0.08	C
5.0	706	2.9	0.04	C	620	5.8	0.08	C
11.0	679	2.1	0.03	C	650	5.0	0.05	C

$I_{BF} = 0.50$

	T = 25 °C				T = -57 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	568	0.49	21.3	A	420	-	0.78	B
0.10	462	9.4	2.2	B	380	11.0	0.28	C
0.20	494	10.2	0.55	C	400	11.0	0.24	C
0.50	488	10.3	0.23	C	500	10.8	0.16	C
1.0	536	10.0	0.15	C	500	10.0	0.12	C
2.0	553	9.1	0.08	C	520	10.0	0.10	C
5.0	581	7.4	0.05	C	400	10.0	0.04	C
11.0	550	6.0	0.03	C	400	9.5	0.06	C

$I_{BF} = 1.0$

	T = 25 °C				T = -44 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	429	11.3	4.1	B	425	14.5	0.40	C
0.10	449	12.9	1.0	B	350	14.3	0.40	C
0.20	474	12.0	0.76	B	300	14.3	0.25	C
0.50	509	13.0	0.26	C	470	13.0	0.24	C
1.0	515	13.4	0.19	C	500	14.0	0.15	C
2.0	[illegible]	12.7	0.12	C	475	14.0	0.08	[illegible]
5.0	[illegible]	11.3	0.06	C	480	[illegible]	[illegible]	C
11.0	491	10.0	0.05	C	490	12.0	0.05	C

I_{BF} = 2.0

	T = 25 °C				T = -54 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	452	14.5	1.5	B	450	17.0	0.50	C
0.10	452	15.8	1.0	C	440	18.0	0.50	C
0.20	466	16.4	0.63	C	440	18.0	0.40	C
0.50	487	16.5	0.36	C	450	18.0	0.30	C
1.0	475	16.0	0.30	C	450	18.0	0.15	C
2.0	493	16.9	0.22	C	450	18.0	0.10	C
5.0	489	14.1	0.08	C	440	17.0	0.15	C
11.0	451	14.2	0.05	C	425	16.0	0.08	C

I_{BF} = 5.0

	T = 25 °C				T = -54 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	444	18.4	0.96	C	420	20.0	0.50	C
0.10	453	19.7	0.95	C	420	20.0	0.50	C
0.20	471	19.9	0.71	C	430	20.0	0.40	C
0.50	495	17.1	0.61	C	430	20.0	0.30	C
1.0	473	19.0	0.47	C	440	20.0	0.25	C
2.0	478	20.0	0.29	C	420	20.0	–	C
5.0	452	18.5	0.12	C	420	20.0	–	C
11.0	405	15.7	0.06	C				

I_{BF} = 11.0

	T = 25 °C				T = -54 °C			
I_{BR}	V_{SB}	I_{SB}	t_{SB}	Type	V_{SB}	I_{SB}	t_{SB}	Type
0.05	442	19.6	1.1	C	420	20.0	0.50	C
0.10	448	19.3	0.85	C	420	20.0	0.50	C
0.20	460	19.7	0.75	C	420	20.0	0.20	C
0.50	463	19.8	0.57	C	430	20.0	0.20	C
1.0	464	19.6	0.22	C	430	20.0	0.20	C
2.0	[illegible]	[illegible]	[illegible]	C	420	20.0	0.15	C
5.0	[illegible]	[illegible]	[illegible]	C	400	20.0	0.10	C
11.0	[illegible]	[illegible]	[illegible]	C	350	20.0	–	

ENERGY AND SECOND BREAKDOWN

Voltage and current waveforms were digitized on the graphics tablet and stored on disks. These data were then processed to obtain a voltage-current product, which was integrated numerically to determine the energy delivered by the load inductance to the collector during turn-off. The energy was then examined as a function of the time to second breakdown, t_{SB}, which is defined as the interval between the time at which the collector-emitter voltage is at 10% of the voltage at second breakdown, V_{SB}, and the time at which V_{CE} falls abruptly. The delay time, t_d, is the interval between the time at which the monostable multivibrator generating the reverse base current pulse is triggered and the time at which the collector-emitter voltage increases to 10% of its peak value; this is somewhat different from the usual definition of delay time, but is more consistent with the time to second breakdown.

The energy vs. t_{SB} data were plotted several ways: using all breakdown data, by second breakdown type, and with forward base current as a parameter. Figures 14 through 25 are plots of energy deposited at the collector at room temperature vs. time to second breakdown for Device Number 19. These are quite typical of the data for the other three devices. It is to be noted that Type C behavior predominates, and that Type B is uncommon. As forward base current is increased, the energy curves are shifted up somewhat.

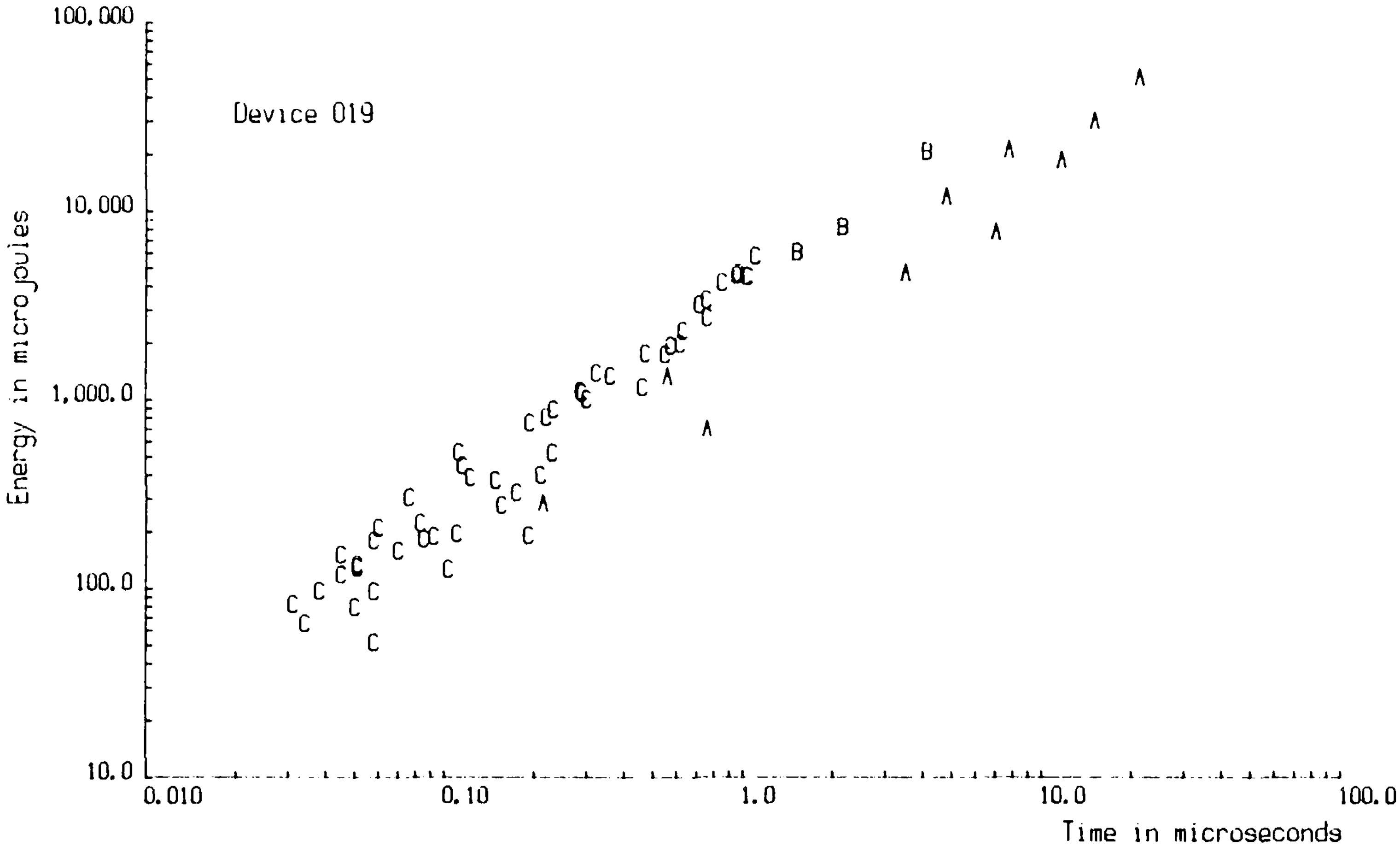


Figure 14. Energy dissipated at the collector at room temprature vs. time to second breakdown for all types of second breakdown (Device Number 19) (A = Type A, B = Type B, C = Type C).

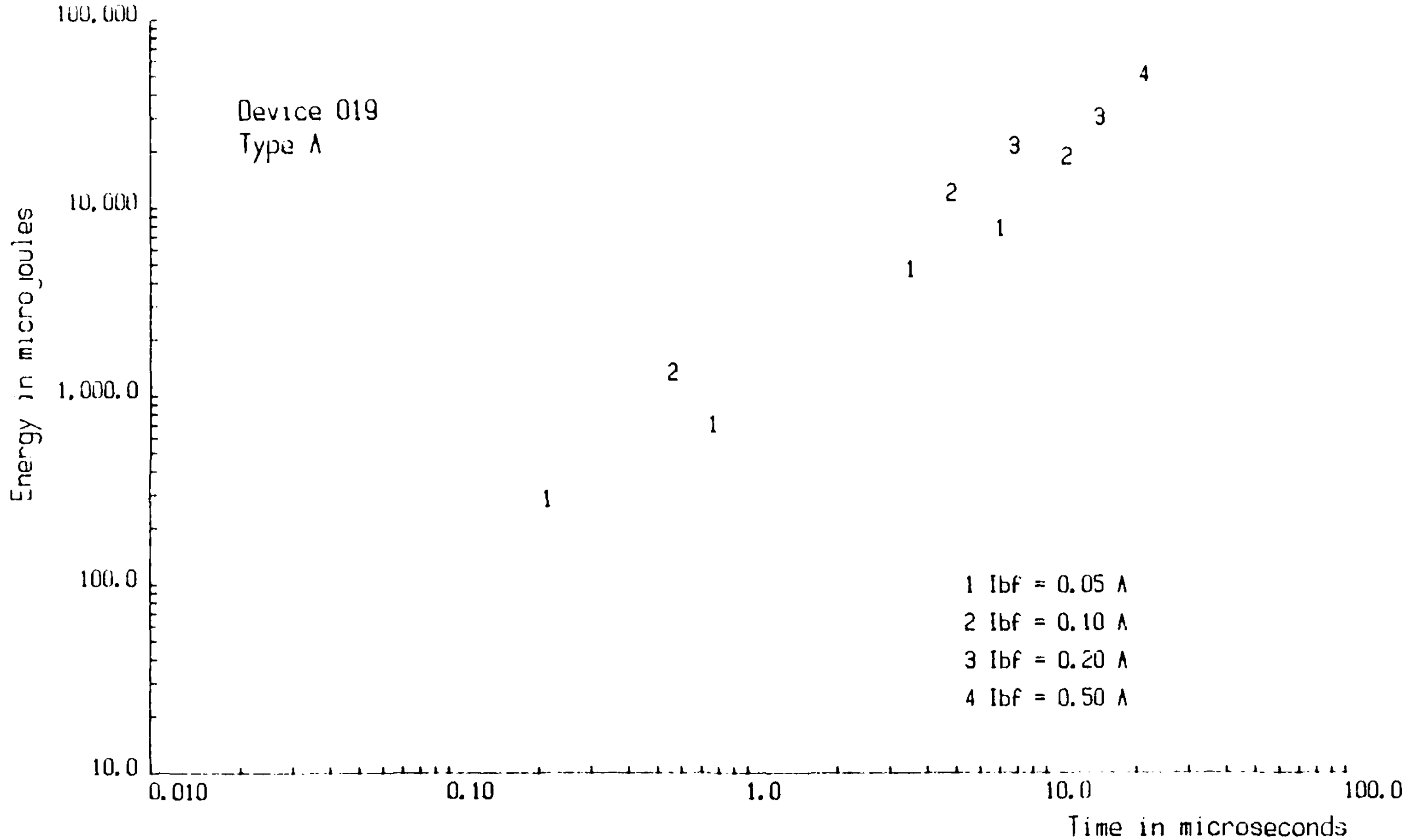


Figure 15. Energy dissipated at the collector at room temperature vs. time to second breakdown for Type A breakdown (Device Number 19).

Table 3.

SUMMARY OF THE RESULTS OF BEST FITS TO THE ENERGY *VS.* TIME TO SECOND BREAKDOWN DATA FOR DEVICE NUMBER 26

Plot	a	b
All Types	2175	1.00
Type A	911	1.32
Type B	-	-
Type C	2910	1.17
I_{BF} = 0.05 A	661	0.95
I_{BF} = 0.10 A	1389	0.92
I_{BF} = 0.20 A	2004	0.97
I_{BF} = 0.50 A	2059	1.02
I_{BF} = 1.0 A	3135	1.24
I_{BF} = 2.0 A	2987	1.14
I_{BF} = 5.0 A	3212	1.02
I_{BF} = 11.0 A	3452	1.04

Table 2.

SUMMARY OF THE RESULTS OF BEST FITS TO THE ENERGY VS. TIME TO SECOND BREAKDOWN DATA FOR DEVICE NUMBER 19

Plot	a	b
All Types	2824	1.03
Type A	1547	1.09
Type B	3431	1.25
Type C	3651	1.12
I_{BF} = 0.05 A	1187	0.98
I_{BF} = 0.10 A	2839	1.03
I_{BF} = 0.20 A	2733	1.01
I_{BF} = 0.50 A	2791	1.02
I_{BF} = 1.0 A	4228	1.12
I_{BF} = 2.0 A	4055	1.09
I_{BF} = 5.0 A	4321	1.08
I_{BF} = 11.0 A	4619	1.08

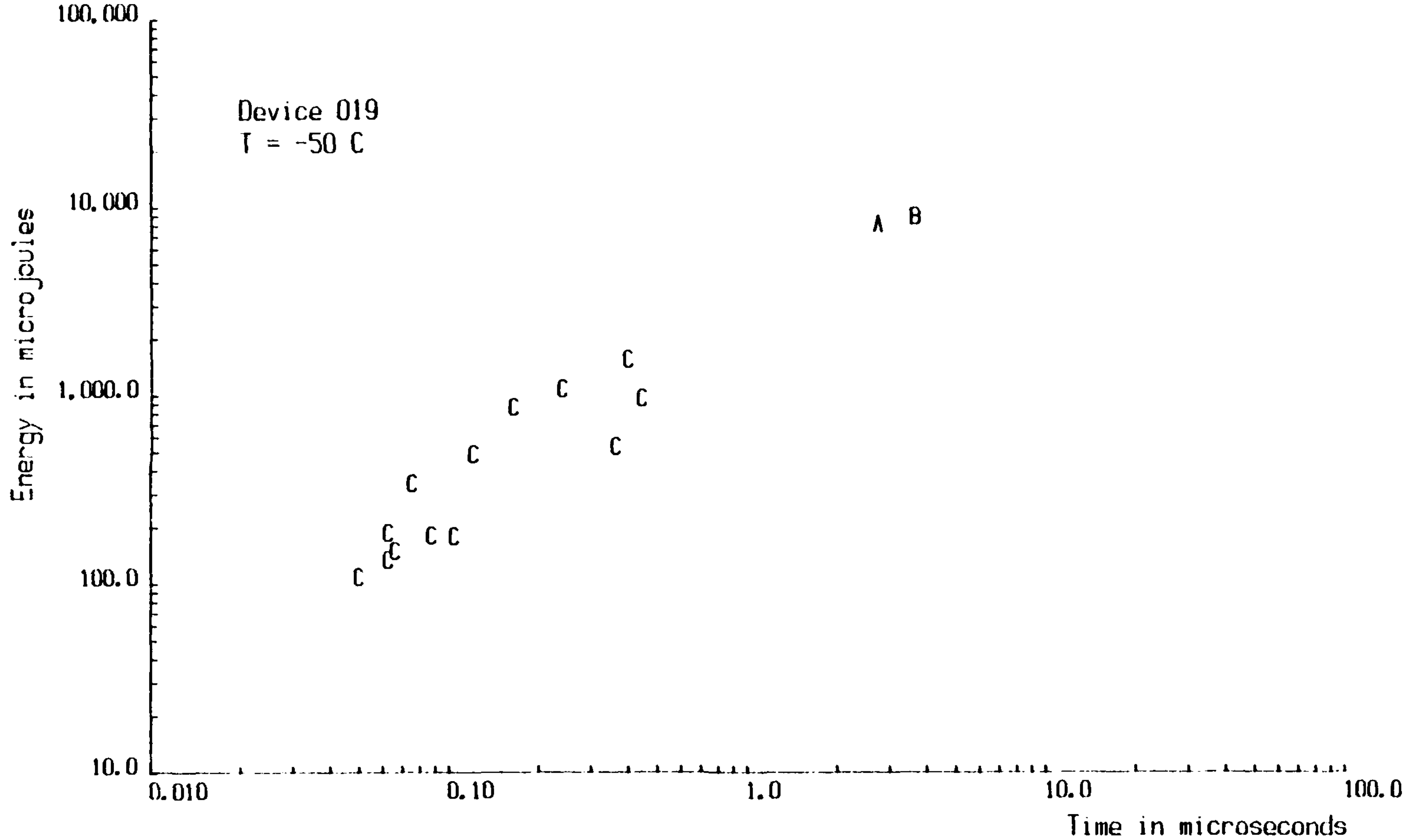


Figure 26. Energy dissipated at the collector at -50 °C vs. time to second breakdown for all types of second breakdown (Device Number 19) (A = Type A, B = Type B, C = Type C).

This effect will be discussed below. The highest energies are delivered to the collector for Type A breakdowns; Type B breakdowns represent an intermediate energy range, and Type C breakdowns, somewhat lower energies. Because device characteristics changed significantly during the low temperature measurements, it was not practicable to digitize and process all the low temperature data. However, one of the devices (Number 19) appeared to have undergone less degradation than the others, so a partial characterization was made for it. The results are shown in Figure 26.

The results of the best fits, $E_{SB} = at_{SB}^{b}$, to the room temperature data, are summarized in Tables 2 through 5. The best fit to the low temperature data of Figure 26 is the relationship $E_{SB} = 3451t_{SB}^{1.053}$. It is clear that the relationship between E_{SB} and t_{SB} is essentially linear for all cases. Heating, which requires a $t^{1/2}$ dependence, is excluded as an initiating mechanism for second breakdown, at least for the Unitrode devices, and perhaps for double-diffused epitaxial devices generally.

The upward shifts in the energy curves which were noted above were examined in terms of the dependence on forward base current of the coefficient, a, in the E_{SB} vs. t_{SB} fits. Figure 27 is a plot of a vs. I_{FB}; these data were fit with a straight line, a power curve, an exponential, and a logarithmic curve. The data were best fit with the logarithmic curve, $a = a' + b'\ln I_{BF}$; the results of the fit are sum-

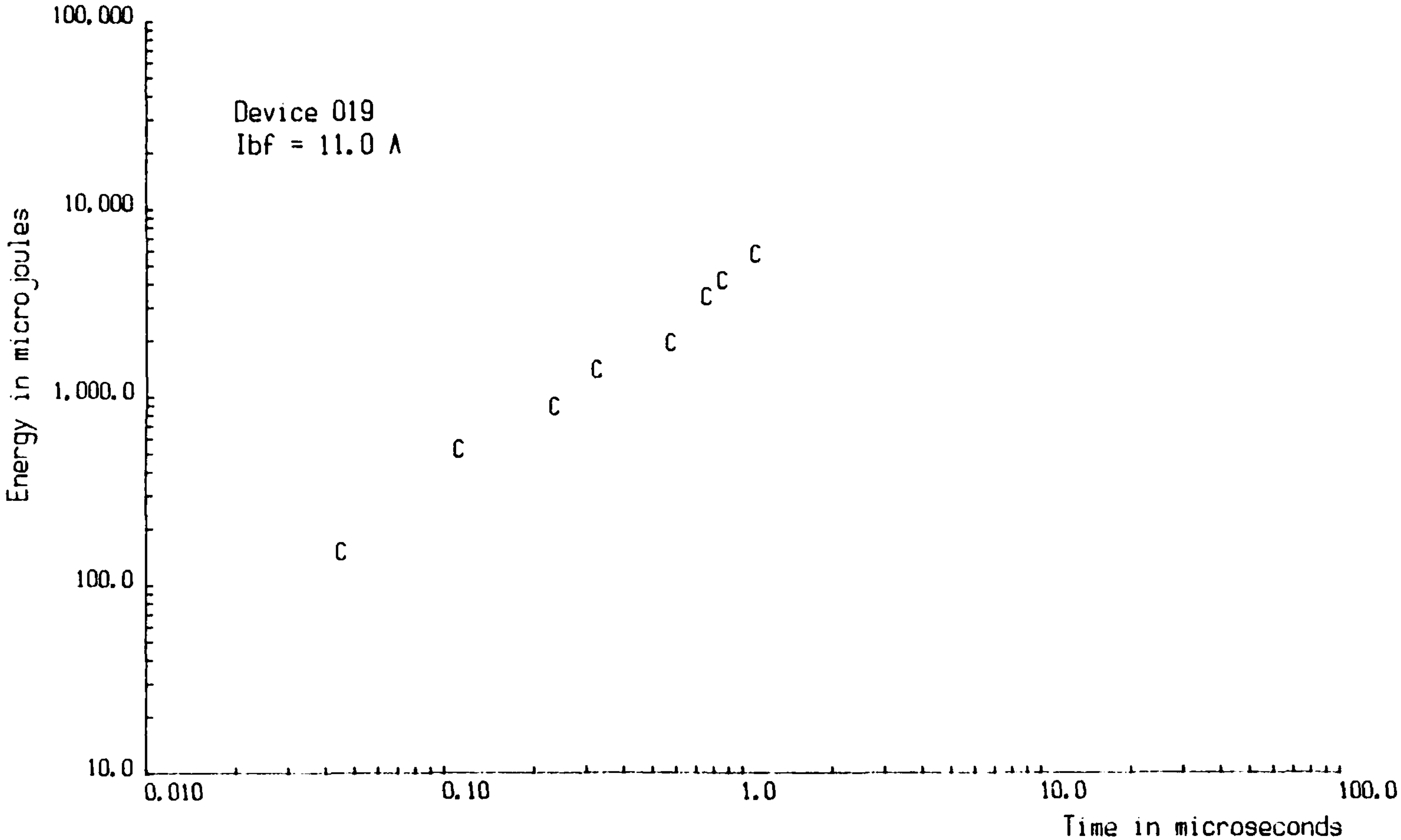


Figure 25. Energy dissipated at the collector at room temperature vs. time to second breakdown for I_{BF} = 11.0 A (Device Number 19) (C = Type C).

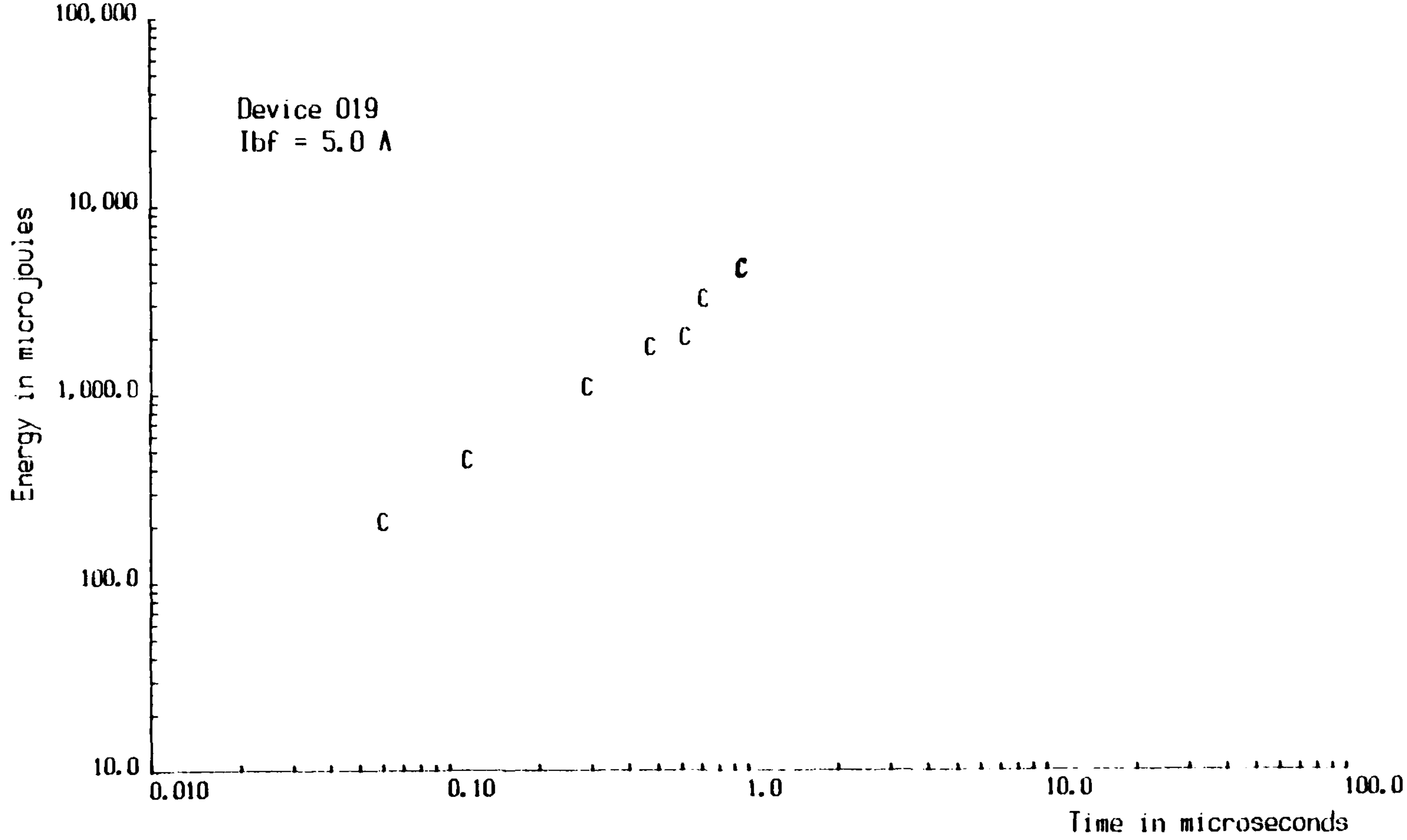


Figure 24. Energy dissipated at the collector at room temperature vs. time to second breakdown for I_{BF} = 5.0 A (Device Number 19) (C = Type C).

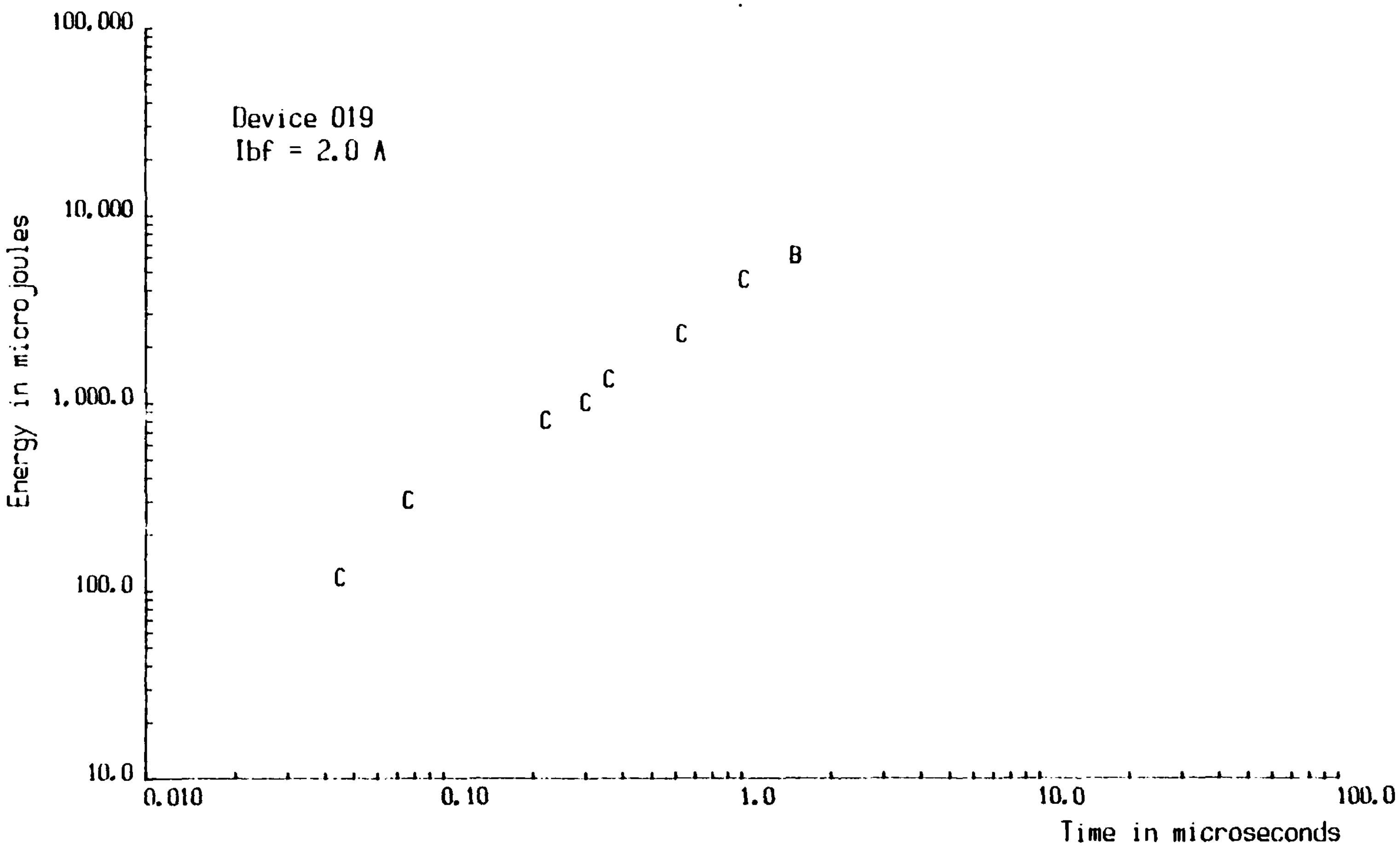


Figure 23. Energy dissipated at the collector at room temperature *vs.* time to second breakdown for I_{BF} = 2.0 A (Device Number 19)(B = Type B, C = Type C).

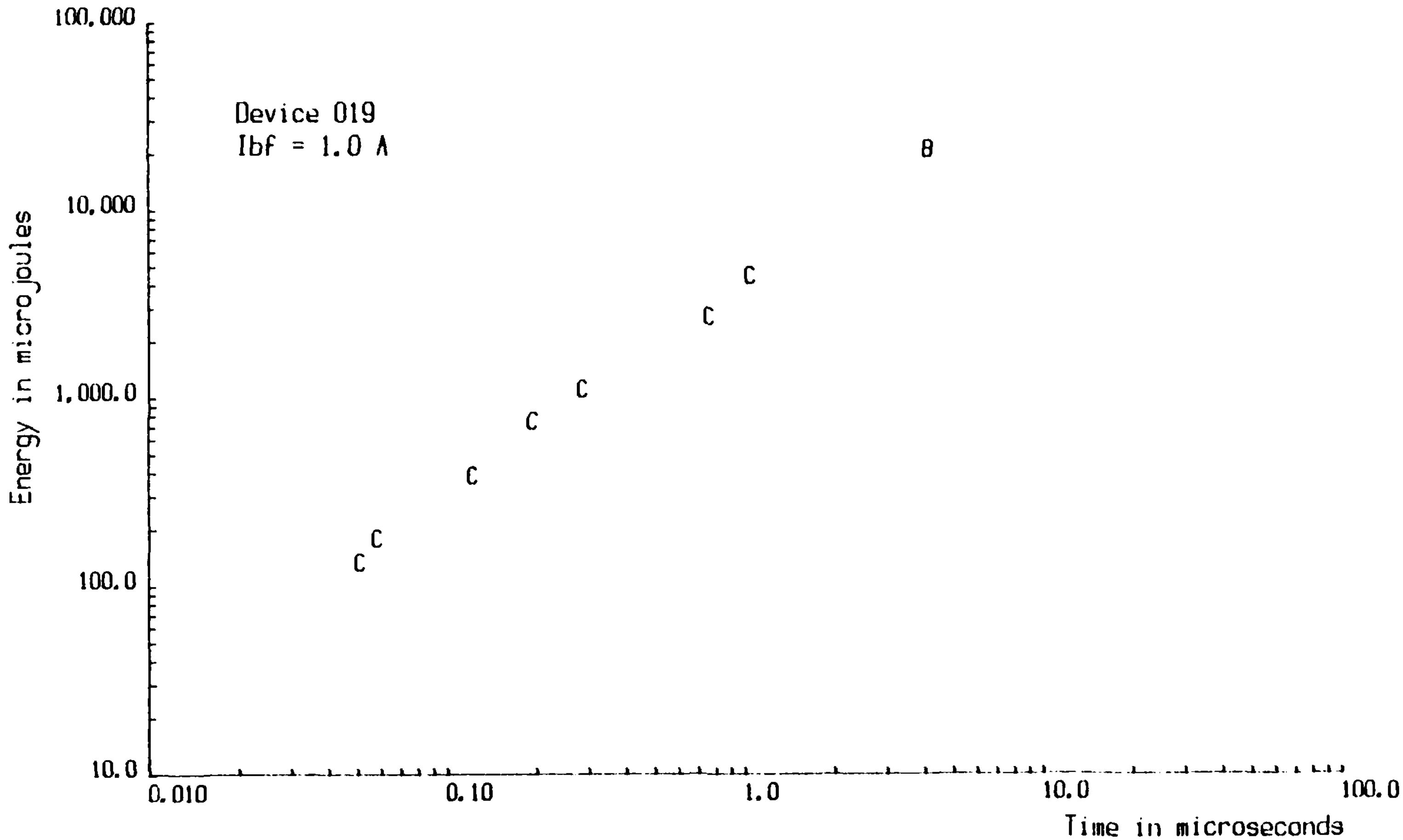


Figure 22. Energy dissipated at the collector at room temperature vs. time to second breakdown for I_{BF} = 1.0 A (Device Number 19) (B = Type B, C = Type C).

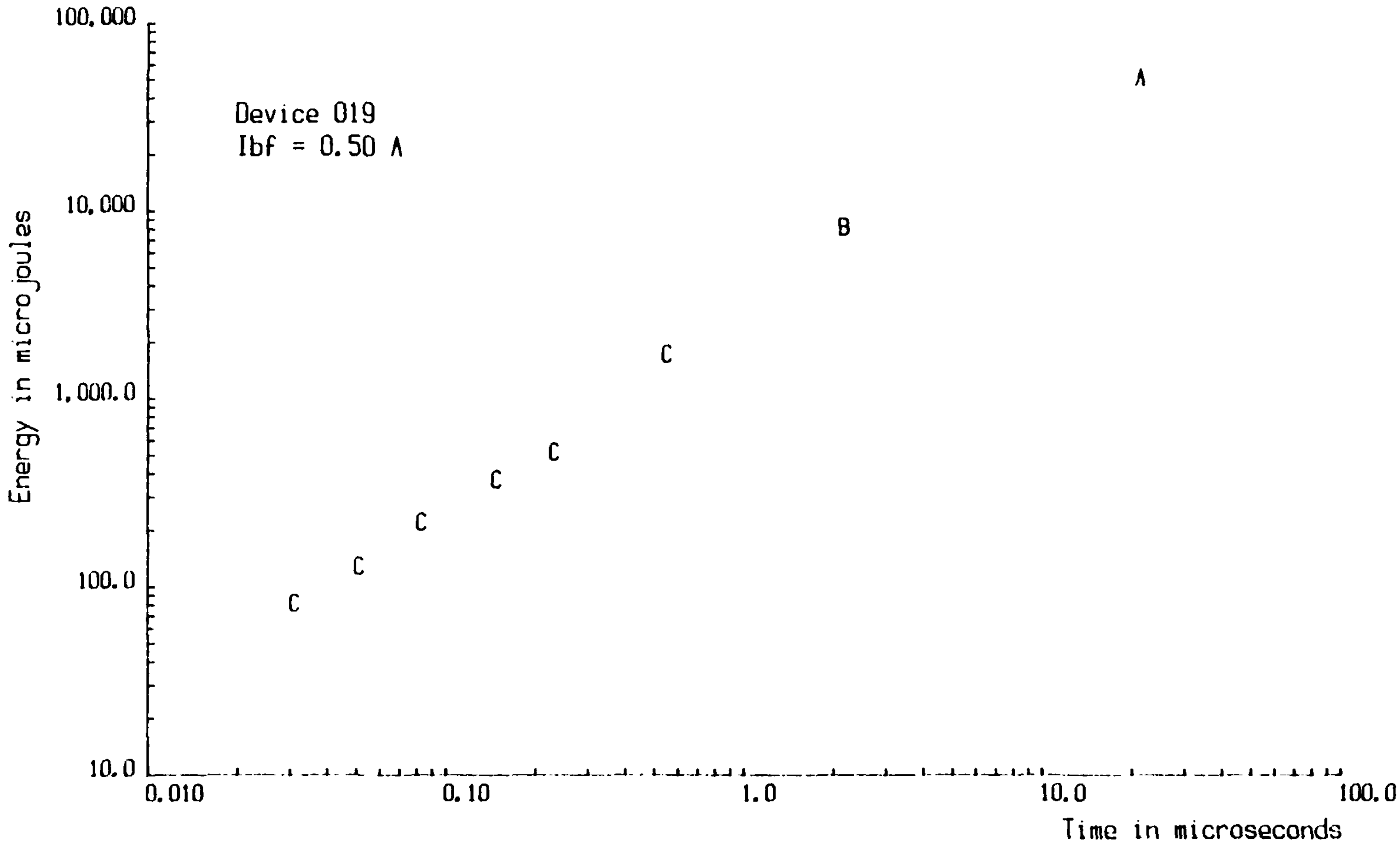


Figure 21. Energy dissipated at the collector at room temperature vs. time to second breakdown for I_{BF} = 0.50 A (Device Number 19) (A = Type A, B = Type B, C = Type C).

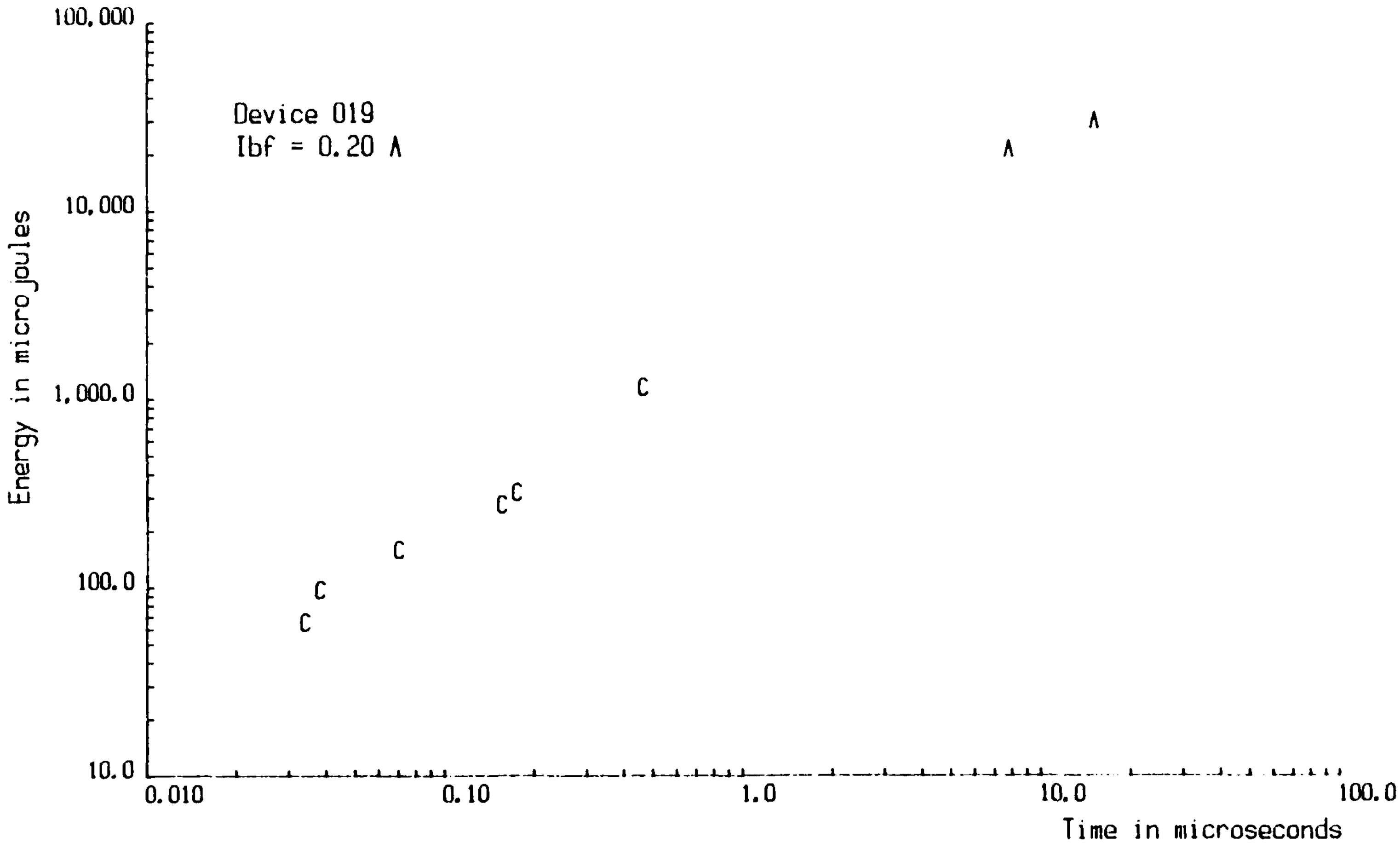


Figure 20. Energy dissipated at the collector at room temperature vs. time to second breakdown for I_{BF} = 0.20 A (Device Number 19) (A = Type A, C = Type C).

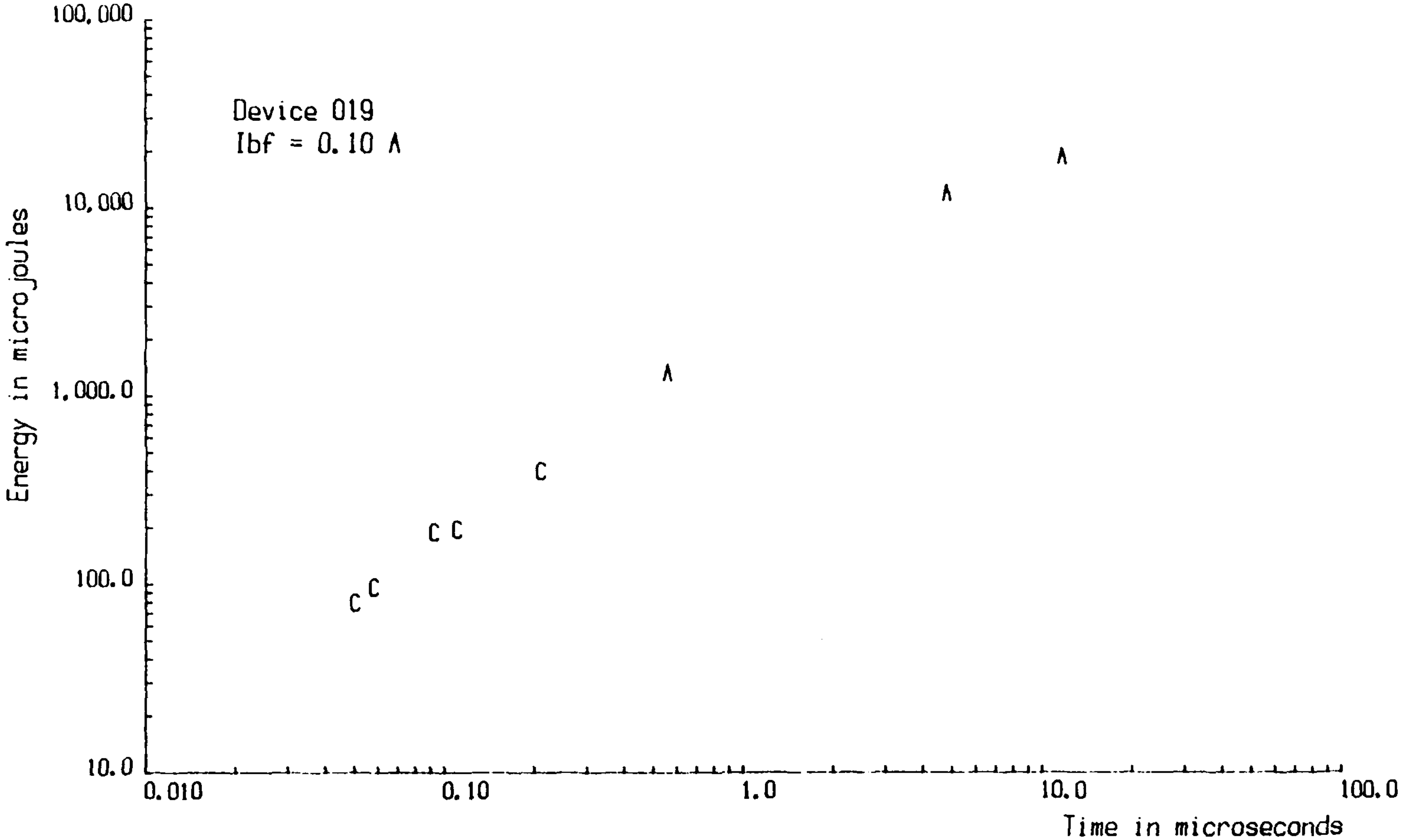


Figure 19. Energy dissipated at the collector at room temperat-ure vs. time to second breakdown for I_{BF} = 0.10 A (Device Number 19) (A = Type A, C = Type C).

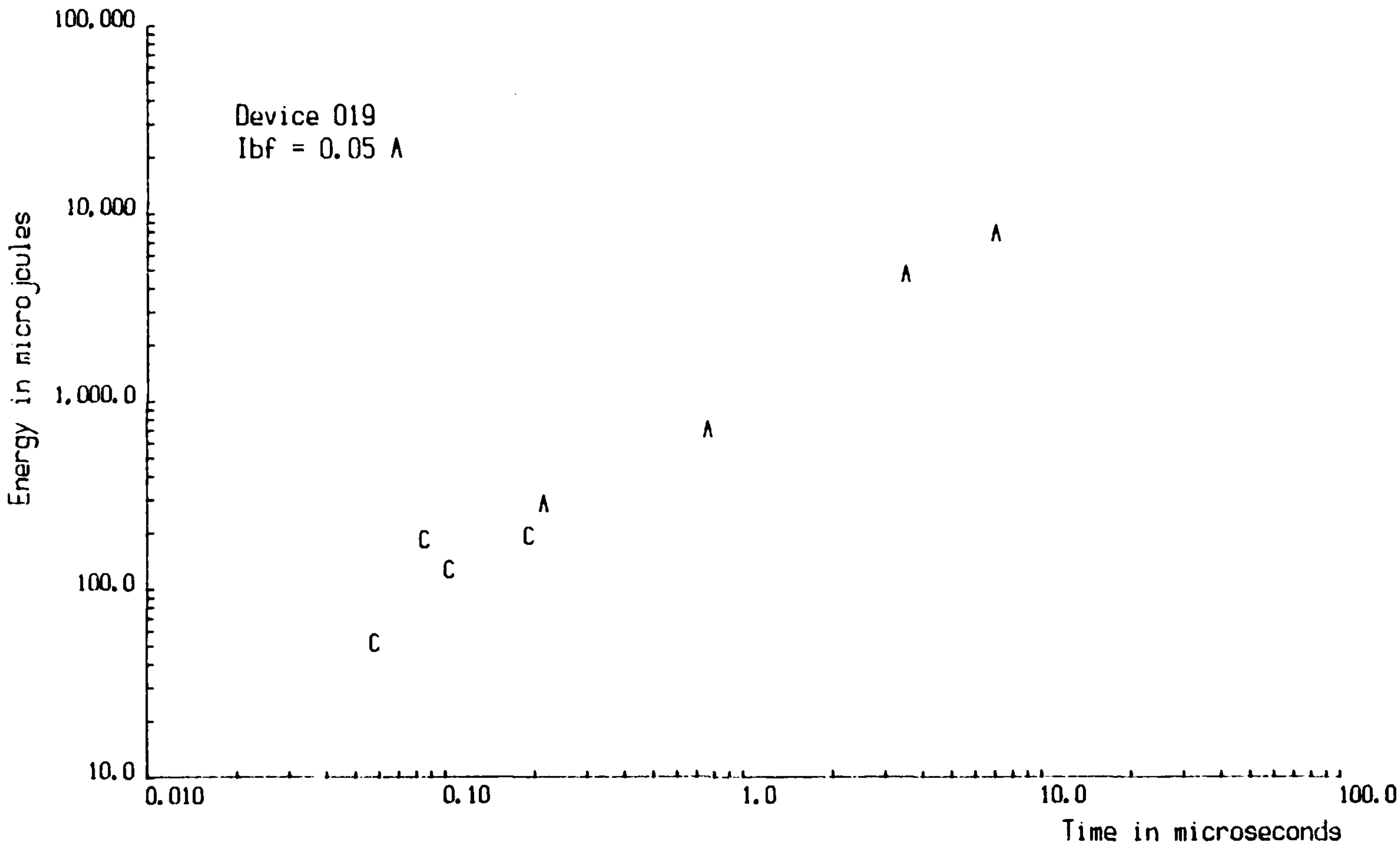


Figure 18. Energy dissipated at the collector at room temperature vs. time to second breakdown for I_{BF} = 0.05 A (Device Number 19)(A = Type A, C = Type C).

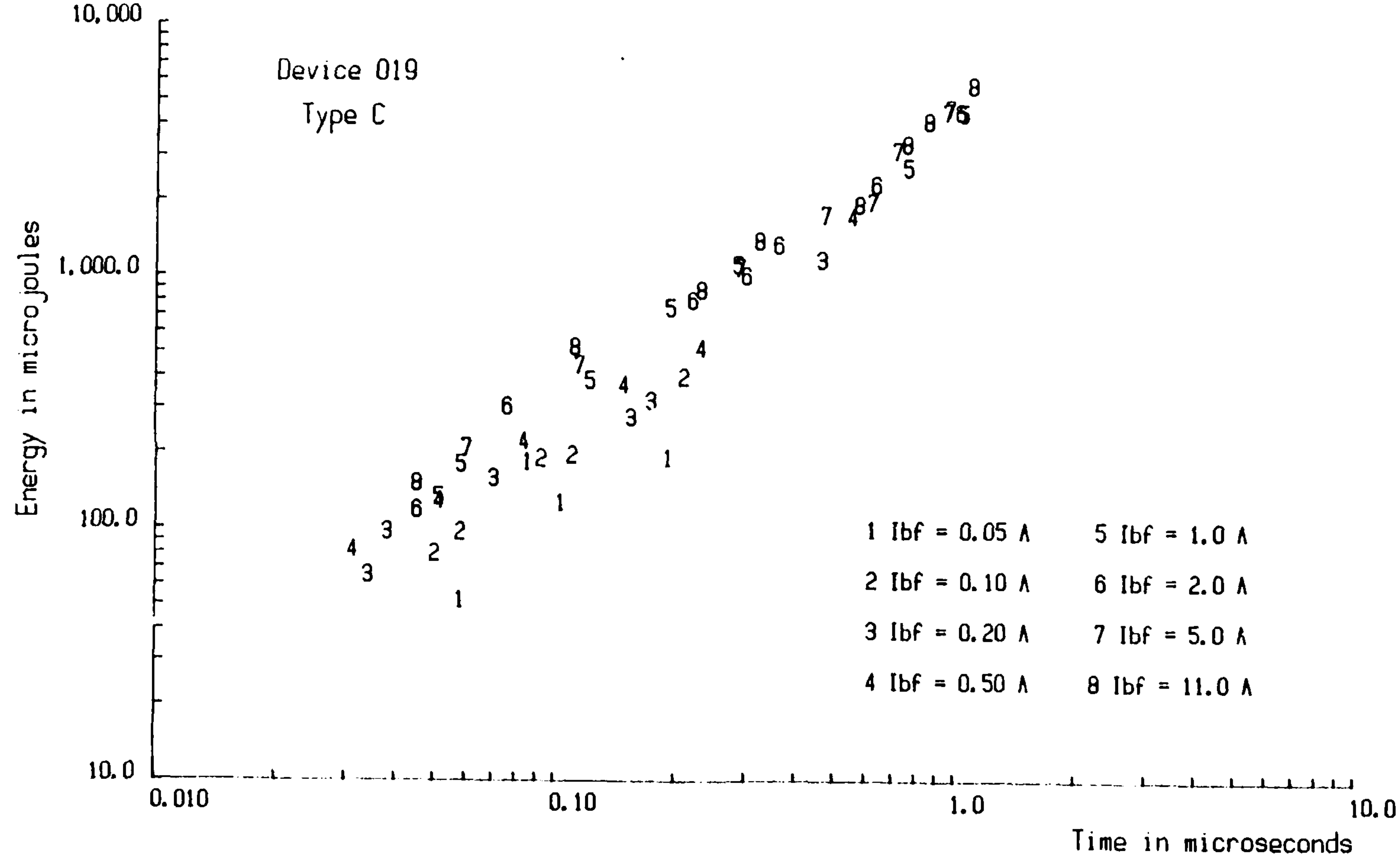


Figure 17. Energy dissipated at the collector at room temperature vs. time to second breakdown for Type C breakdown (Device Number 19).

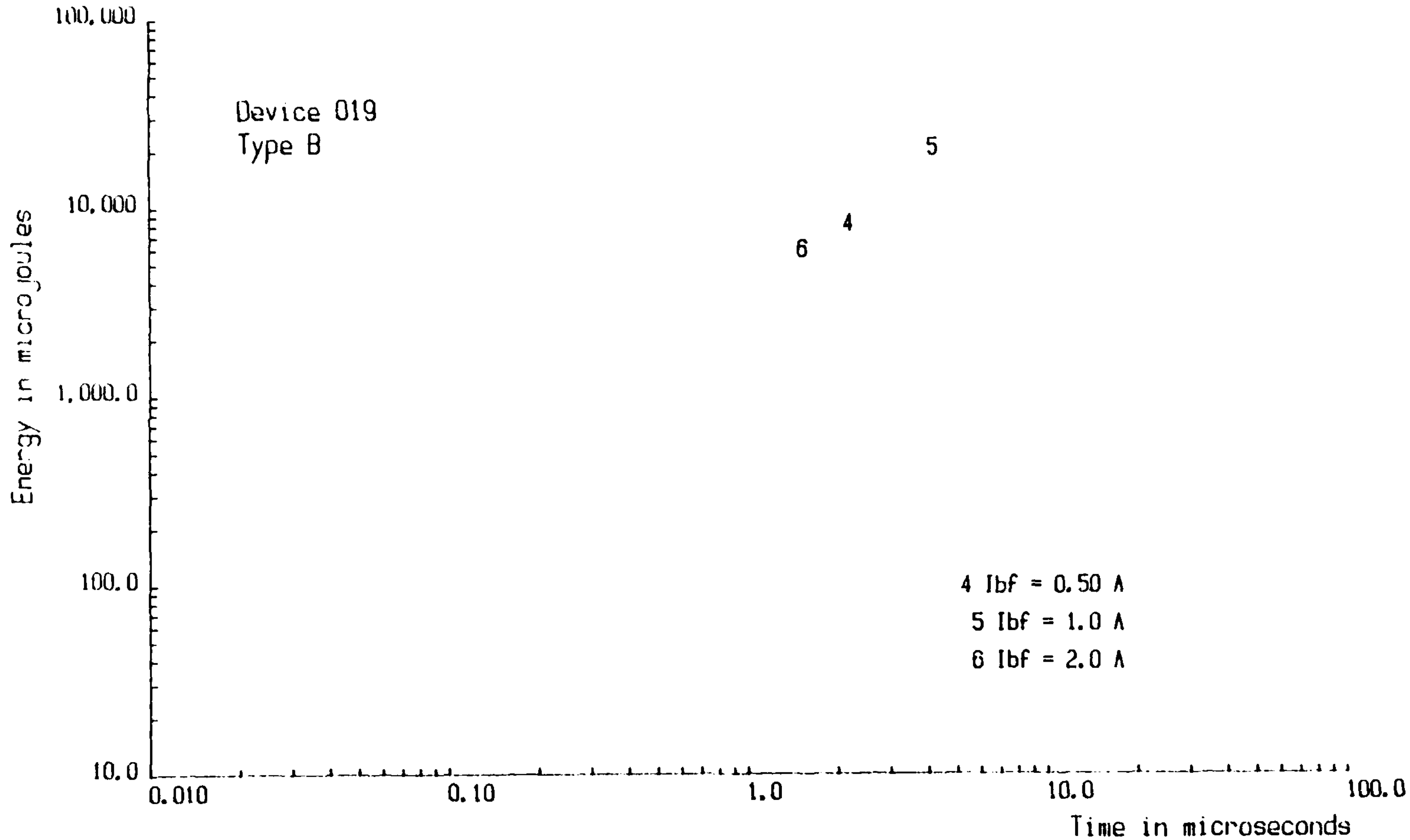


Figure 16. Energy dissipated at the collector at room temperature vs. time to second breakdown for Type B breakdown (Device Number 19).

Table 4.

SUMMARY OF THE RESULTS OF BEST FITS TO THE ENERGY VS. TIME TO SECOND BREAKDOWN DATA FOR DEVICE NUMBER 36

Plot	a	b
All Types	2248	1.00
Type A	1168	1.08
Type B	-	-
Type C	3959	1.28
I_{BF} = 0.05 A	628	1.03
I_{BF} = 0.10 A	1511	1.01
I_{BF} = 0.20 A	2237	1.05
I_{BF} = 0.50 A	2398	1.04
I_{BF} = 1.0 A	4015	1.18
I_{BF} = 2.0 A	3425	1.01
I_{BF} = 5.0 A	3468	0.93
I_{BF} = 11.0 A	4203	0.96

Table 5.

SUMMARY OF THE RESULTS OF BEST FITS TO THE ENERGY VS. TIME TO SECOND BREAKDOWN DATA FOR DEVICE NUMBER 37

Plot	a	b
All Types	2387	1.04
Type A	1370	1.10
Type B	-	-
Type C	3014	1.16
I_{BF} = 0.05 A	965	1.09
I_{BF} = 0.10 A	1351	1.03
I_{BF} = 0.20 A	1764	1.05
I_{BF} = 0.50 A	2213	1.00
I_{BF} = 1.0 A	3374	1.18
I_{BF} = 2.0 A	2667	1.05
I_{BF} = 5.0 A	3091	0.89
I_{BF} = 11.0 A	3423	0.90

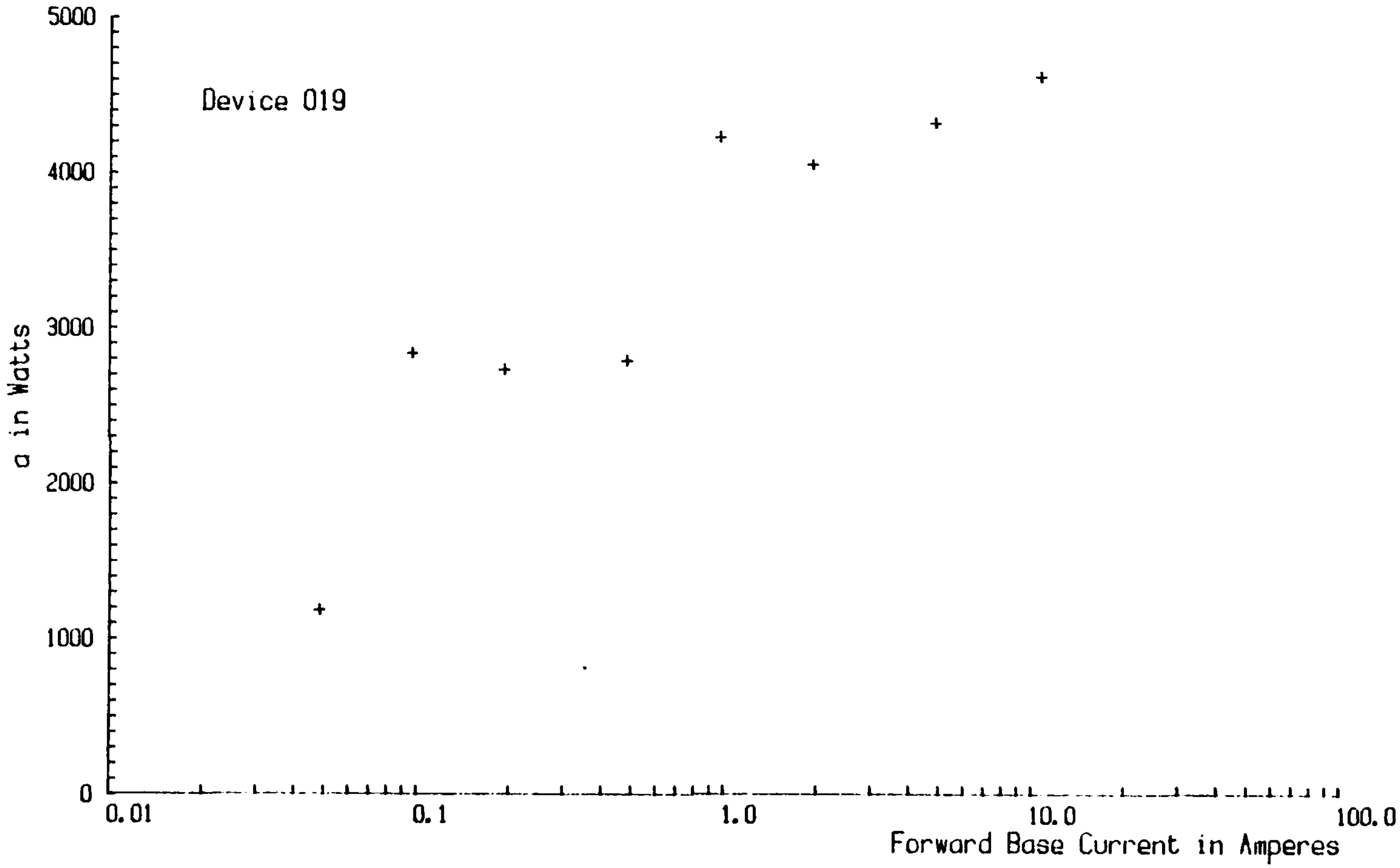


Figure 27. Plot of the coefficient, a, vs. forward base current for Device Number 19.

marized for the four devices in Table 6. The logarithmic fit indicates only a weak dependence of the energy on forward current; what is more interesting is the relationship between a', b' and the mask types. The respective constants are somewhat larger for the NE masks than the NH masks, suggesting that a' and b' may be related to emitter stripe geometry and die area.

Table 6.

SUMMARY OF THE RESULTS OF LOGARITHMIC CURVE FITS TO THE COEFFICIENT, a, VS. I_{BF}

Device	Mask Type	a'	b'
019	NE	3550	562
026	NH	2543	499
036	NE	2922	639
037	NH	2522	458

V. CONCLUSIONS

The room temperature results indicate that, for the devices tested here, and perhaps for all double-diffused epitaxial power transistors, a thermal initiation mechanism for second breakdown is excluded. This is an important result, and its generality should be examined by testing similar structures, both double-diffused epitaxial and triple-diffused, from other manufacturers. Comparisons should be made with single-diffused transistors (for which Type C second breakdown should be confirmed) to verify the linear relationship between energy and time to second breakdown at these temperatures, and particularly to study the apparently rapid degradation at lower temperatures. Finally, the data entry and analysis system should be completed, to permit the rapid conditioning of the large quantity of data required for a general device analysis, and to establish procedures and criteria for acceptance of low vulnerability devices.

REFERENCES

1. D. W. Berning, Semiconductor Measurement Technology: A reverse-bias safe operating area transistor tester, NBS Special Publication 400-54, April, 1979.

2. W. M. Portnoy, Reverse Bias Second Breakdown in Power Switching Transistors, Air Force Weapons Laboratory Final Report AFWL-TR-82-139, May, 1983.

3. D. L. Blackburn, National Bureau of Standards, private communication, December 8, 1983.

APPENDIX A

Program MASTER

```
10 REM *
20 REM *
30 REM *  MASTER CONTROL
40 REM *     INTERFACE ROUTINE
50 REM *
60 REM *Copyright:  9/26/83
70 REM * gandalf software, inc.
80 REM * Chuck Graves, Wizard
90 REM *
100 REM *
105 OPTION BASE 1@ CLEAR
110 OUTPUT 706 ;"IN"
115 GOSUB 5600
120 DISP "How many curves will be plotted?"
130 INPUT Q
140 IF Q>0 AND Q<7 THEN 170
150 DISP "Please choose a number 1 to 6."
160 GOTO 130
170 INTEGER T(3),P(10),U(4),V(4),X(6,150),Y(6,150)
175 DIM P$[25],T$[50]
180 CLEAR @ OUTPUT 706 ;"BP42,125,5"
185 GOSUB 5300
190 DISP "Please digitize the corners of"
200 DISP "the graph grid in the following"
210 DISP "order:  upper left, upper right,"
220 DISP "lower left, and lower right."
230 FOR I1=1 TO 4
240 GOSUB 1000
250 IF NOT S THEN 240
260 U(I1)=T(1)
270 V(I1)=T(2)
280 NEXT I1
295 GOSUB 4500
300 FOR J=1 TO Q
310 DISP "Begin digitizing curve";J;"."
320 P1=J
330 FOR I=1 TO 150
340 GOSUB 1900
350 IF P(J)=151 THEN DISP "Storage file is full (150 pts
.)." @ WAIT 2000
360 NEXT I
370 NEXT J
380 CLEAR
390 DISP "The digitization process is"
395 DISP "complete.  If you would like to"
400 DISP "do anything else, please"
410 DISP "digitize the desired softkey."
420 GOSUB 1900
430 IF K=5 AND H$="PLOT" THEN 460
440 IF K=4 AND H$="PLOT" THEN 460
450 GOTO 390
```

```
460 CLEAR
470 DISP "Reload the plotter with paper."
480 DISP "Press CONTINUE when ready."
490 PAUSE
495 PLOTTER IS 705
500 CLEAR
505 SCALE 0,12032,0,8831
510 DISP "Do you want a grid on the plot?" @ DISP "(Y/N)
"
520 INPUT G$
530 DISP "How many horizontal divisicns?"
540 INPUT U1
550 DISP @ DISP "How much is each division?"
560 DISP "(magnitude, unit) 5 mV is 5, mV."
570 INPUT U2,U2$
580 CLEAR
590 DISP "How many vertical divisions?"
600 INPUT V1
610 DISP @ DISP "How much is each division?"
620 DISP "(magnitude, unit) 5 mV is 5, mV."
630 INPUT V2,V2$
640 CLEAR
650 DISP "What is the horizontal label?"
660 INPUT U$
670 DISP @ DISP "What is the vertical label?"
680 INPUT V$
685 LORG 6 @ CSIZE (H*(U(2)-U(1))/8831*100+10)/20,.5
690 LOCATE 10,H*(U(2)-U(1))/8831*100+10,10,H*(V(1)-V(3))
/8831*100+10
692 FRAME
695 SCALE 0,U1*U2,0,V1*V2
700 IF G$="Y" THEN 730
710 AXES U2,V2,0,0,1,1,5
720 GOTO 731
730 GRID U2,V2,0,0,1,1,1
731 FOR I1=1 TO U1
732 MOVE I1*U2,-(V2/10)
733 LABEL VAL$(I1*U2)
734 NEXT I1
735 LORG 8
736 FOR I2=1 TO V1
737 MOVE -(U2/10),I2*V2
738 LABEL VAL$(I2*V2)
739 NEXT I2
740 IF Q<=1 THEN 758
741 DISP @ DISP "What is the second vertical" @ DISP "la
bel?"
742 INPUT V1$@ CLEAR
743 DISP @ DISP "How much is each division"
744 DISP "on the second vertical axis?"
745 DISP "(magntude, unit) 5 mV is 5, mV."
```

```
746 INPUT V3, V3$
747 LORG 2
748 FOR I1=1 TO V1
749 MOVE U1*U2+U2/10, I1*V2
750 LABEL VAL$(I1*V3)
751 NEXT I1
752 DEG @ LDIR 90
753 LORG 6 @ CSIZE (H*(U(2)-U(1))/8831*100+10)/14,.5
754 MOVE U1*U2*1.1,.5*V1*V2
755 LABEL V1$;" (";V3$;")"
756 RAD @ LDIR 0
758 LORG 6 @ CSIZE (H*(U(2)-U(1))/8831*100+10)/14,.5
759 MOVE .5*U1*U2,-(V1*V2/10)
760 LABEL U$;" (";U2$;")"
770 DEG @ LDIR 90 @ LORG 4
780 MOVE -(U1*U2/10),.5*V1*V2
790 LABEL V$;" (";V2$;")"
795 RAD @ LDIR 0
800 N=U1*U2/(U(2)-U(1))
810 O=V1*V2/(V(1)-V(3))
820 FOR I1=1 TO Q
830 MOVE (X(I1,1)-U(1))*N,(Y(I1,1)-V(3))*O
840 FOR I2=1 TO P(I1)-1
850 DRAW (X(I1,I2)-U(1))*N,(Y(I1,I2)-V(3))*O
860 NEXT I2
870 NEXT I1
871 DISP @ DISP "How many lines does the main"
872 DISP "title have?"
873 INPUT T1
874 LORG 4
875 FOR I1=1 TO T1
876 DISP @ DISP "What is line";I1;"?" @ INPUT T$
877 DISP @ DISP "Where do you want line";I1 @ DISP "prin
ted?"
878 DISP "(Give y-coordinate from the" @ DISP "graph.)"
879 INPUT T2
880 MOVE U1*U2*.5,T2
881 LABEL T$
882 NEXT I1
885 DISP "Would you like another copy?" @ DISP "(Y/N)"
890 INPUT Q$
900 IF Q$="Y" THEN 685
910 CLEAR
920 DISP "Are you finished? (Y/N)"
930 INPUT Q$
940 IF Q$="Y" THEN CLEAR @ GOTO 960
```

```
950 GOTO 390
960 DISP "Would you like to digitize"
965 DISP "another set of curves? (Y/N)"
970 INPUT Q$
975 IF Q$="Y" THEN 120
980 CHAIN "SMILE:D700"
990 END
1000 REM *
1010 REM *
1020 REM *  DIGITIZER SUBROUTINE
1030 REM *     A) CHECK STATUS;
1040 REM *     B) GET POINTS; OR.
1050 REM *     C) GET SOFTKEYS.
1060 REM *
1070 REM *
1080 OUTPUT 706 ;"SG;DP"
1090 B=7 @ B$="RS" @ B1=1
1100 P$="BP24,125,5;BP36,125,5"
1110 GOSUB 1200 @ REM *  SOFTKEY?
1120 IF S THEN 1160
1130 B=2 @ B$="OD" @ B1=3
1140 P$="BP36,125,5"
1150 GOSUB 1200 @ REM *  POINT?
1160 RETURN
1200 REM *
1210 REM *
1220 REM *  STATUS SUBROUTINE
1230 REM *     A) CHECK SOFTKEY;
1240 REM *     B) CHECK POINT.
1250 REM *
1260 REM *
1270 OUTPUT 706 ;"OS" @ REM * READY?
1280 ENTER 706 ; S
1290 S=BIT(S,B)
1300 IF NOT S THEN GOTO 1370 @ REM * NO. EXIT.
1310 OUTPUT 706 ;B$ @ REM * YES. GET.
1320 IF B1=3 THEN 1350
1330 ENTER 706 ; T(1)
1340 GOTO 1360
1350 ENTER 706 ; T(1),T(2),T(3)
1360 OUTPUT 706 ;P$
1370 RETURN
1900 REM *
1910 REM *
1920 REM *  ACTIVE SUBROUTINE
1930 REM *     A) ESTABLISH ACTIVE FILES;
1940 REM *     B) STORE DATA.
1950 REM *
1960 REM *
```

```
1970 GOSUB 1000 @ REM * DATA?
1980 IF NOT S THEN GOTO 1970 @ REM * NO. WAIT.
1990 IF B=2 THEN GOTO 2030 @ REM * YES.
2000 K=T(1)
2010 ON K GOSUB 3100,3200,3300,3520,3600,5900,3800,3800,
3800,3800,3800,3800,3800,3800,3800,3800
2020 GOTO 2070
2030 GOSUB 4700
2040 X(P1,P(J))=T(1)
2050 Y(P1,P(J))=T(2)
2060 P(J)=P(J)+1
2070 RETURN
2100 REM *
2110 REM *
2120 REM *  FILE SUBROUTINE
2130 REM *     A) CREATE DATA FILES.
2140 REM *     B) OPENS DATA FILES.
2150 REM *
2160 REM *
2170 CREATE "X"&VAL$(Q),150*Q+10,8
2180 CREATE "Y"&VAL$(Q),150*Q,8
2190 ASSIGN# 1 TO "X"&VAL$(Q)
2200 ASSIGN# 2 TO "Y"&VAL$(Q)
2210 RETURN
2700 REM *
2710 REM *
2720 REM *  MASS STORAGE SUBROUTINE
2730 REM *     A) ESTABLISH MEDIUM
2740 REM *
2750 IF R$="TAPE" THEN 2780
2755 IF R$="DISK01" THEN 2770
2760 MASS STORAGE IS ":D700"
2765 GOTO 2790
2770 MASS STORAGE IS ":D701"
2775 GOTO 2790
2780 MASS STORAGE IS ":T"
2790 RETURN
2800 REM *
2810 REM *
2820 REM *  STORAGE SUBROUTINE
2830 REM *     A) TRANSFER FROM ACTIVE
2840 REM *        FILE TO STORAGE MEDIUM
2850 REM *        (TAPE OR DISK)
2860 REM *
2870 REM *
2880 FOR I1=1 TO 10
2890 PRINT# 1,I1 ; P(I1)
2300 NEXT I1 @ M=10
```

```
2901 FOR I4=1 TO 4
2902 PRINT# 2,2*I4-1 ; U(I4)
2903 PRINT# 2,2*I4 ; V(I4)
2904 NEXT I4
2910 FOR I2=1 TO P1
2920 FOR I3=1 TO P(I2)-1
2930 M=M+1
2940 PRINT# 1,M ; X(I2,I3)
2950 PRINT# 2,M-2 ; Y(I2,I3)
2960 NEXT I3
2970 NEXT I2
2980 RETURN
3000 REM *
3010 REM *
3020 REM *  SOFTKEY SUBROUTINE
3030 REM *    1) STOP
3040 REM *    2) STORE
3050 REM *    3) LOAD
3060 REM *    4) SCALE
3070 REM *    5) PLOT
3080 REM *    6-16) Not used
3090 REM *
3100 REM *
3110 REM *    1) STOP
3120 REM *
3130 REM *
3140 CLEAR
3150 DISP "Are you finished with this curve?" @ DISP "(Y
/N)"
3160 INPUT A$
3170 IF A$="Y" THEN GOTO 370
3180 RETURN
3190 REM *
3200 REM *
3210 REM *    2) STORE
3220 REM *
3230 REM *
3240 CLEAR
3250 DISP "Where do you want the data" @ DISP "stored? (
TAPE/DISK00/DISK01)"
3260 INPUT R$
3270 GOSUB 2700
3273 GOSUB 2100
3280 GOSUB 2800
3283 GOSUB 4200
3286 GOSUB 5100
3290 RETURN
3300 REM *
3310 REM *
```

```
3260 PRINT "is To=";
3262 YO=.1*(Y(1,P(1)-1)-V(3))+V(3)
3264 MO=(Y(1,I1+1)-Y(1,I1))/(X(1,I1+1)-X(1,I1))
3265 IF YO-Y(1,I1)<0 THEN YO=Y(1,I1)
3266 XO=(YO-Y(1,I1))/MO+X(1,I1)
3268 R1=(XO-U(1))*N
3270 GOSUB 6500
3275 PRINT VAL$(R1);" ";U2$;"." @ PRINT
3277 PRINT "The value of instantaneous"
3279 PRINT VO$[1,Z1(1)];" at To is ";
3280 R1=(YO-V(3))*V1*V2(1)/(V(1)-V(3))
3281 GOSUB 6500
3283 PRINT VAL$(R1);" ";V4$[1,Z(1)];"." @ PRINT
3285 FOR I2=2 TO 4 STEP 2
3287 I3=I2
3289 IF I2=4 THEN I3=6
3290 O=V1*V2(I2)/(V(1)-V(3))^(1+IP((I2-1)/2))
3292 MO=(Y(I3,I1+1)-Y(I3,I1))/(X(I3,I1+1)-X(I3,I1))
3294 YO=(XO-X(1,I1))*MO+Y(I3,I1)
3295 PRINT "The value of instantaneous"
3300 PRINT VO$[Z1(I2-1)+1,Z1(I2)];" at To is ";
3305 IF I2>2 THEN 3325
3310 R1=(YO-V(3))*O
3315 GOSUB 6500
3320 GOTO 3335
3325 R1=YO*O/(K2*(U(2)-U(1)))*N2
3330 GOSUB 6500
3335 PRINT VAL$(R1);" ";V4$[Z(I2-1)+1,Z(I2)];"."
3340 PRINT
3345 NEXT I2
3350 PRINT "The change in ";VO$[Z1(3)+1,Z1(4)];" from "
3355 PRINT "To to second-breakdown is "
3360 R1=(Y(6,P(6)-1)-YO)*O/(K2*(U(2)-U(1)))*N2
3365 GOSUB 6500
3370 PRINT VAL$(R1);" ";V4$[Z(3)+1,Z(4)];"." @ PRINT
3372 PRINT "To to second-breakdown is "
3374 R1=(X(1,P(1)-1)-XO)*N
3376 GOSUB 6500
3377 PRINT VAL$(R1);" ";U2$;"."
3378 RETURN
3380 CLEAR @ GCLEAR @ DISP "Load the printer and press"
3382 DISP "CONTINUE." @ PAUSE
3385 LORG 6 @ CSIZE (H*(U(2)-U(1))/8831*50+10)/19,.3
3390 J=10+IP((I1+1)/4)*60
3395 L=10+FP(I1/2)*100
3400 LOCATE J,H*(U(2)-U(1))/8831*50+J,L,H*(V(1)-V(3))/88
31*50+L
3405 FRAME
3410 SCALE 0,U1*U2,0,V1*V2(I1)
3415 IF G$="Y" THEN 3430
```

```
3015 R3=FNA(V2(3))
3020 N1=V2(3)/(R3*1000^J5) @ V2(3)=R3
3025 K2=IP((V(1)-V(3))^2*(U(2)-U(1))/B)
3030 IF K2>0 THEN K2=1/K2 @ GOTO 3040
3035 K2=IP(B/((V(1)-V(3))^2*(U(2)-U(1))))
3040 V2(4)=K2*V2(1)*V2(2)*V1*U1*U2
3045 R4=FNA(V2(4))
3050 N2=V2(4)/(R4*1000^J5) @ V2(4)=R4
3055 J4(4)=J4(4)+J4(3)-2
3060 GOSUB 3800
3065 CLEAR @ DISP "What is the horizontal label?"
3070 INPUT U$
3075 DISP @ DISP "What is the first vertical"
3080 DISP "label?"
3085 INPUT V0$
3090 DISP @ DISP "What is the second vertical"
3095 DISP "label?"
3100 INPUT V1$
3105 Z1(0)=0 @ Z1(1)=LEN(V0$)
3110 V2$="POWER" @ V3$="ENERGY"
3115 Z1(2)=LEN(V1$)+Z1(1)
3120 Z1(3)=LEN(V2$)+Z1(2)
3125 Z1(4)=LEN(V3$)+Z1(3)
3130 V0$=V0$&V1$&V2$&V3$
3135 N=U1*U2/(U(2)-U(1))
3140 FOR I1=1 TO 4
3145 O=V1*V2(I1)/(V(1)-V(3))^(1+IP((I1-1)/2))
3150 PRINT "The value for instantaneous"
3155 PRINT V0$[Z1(I1-1)+1,Z1(I1)];" at the final point i
s "
3160 IF I1>2 THEN 3180
3165 R1=(Y(I1,P(1)-1)-V(3))*O
3170 GOSUB 6500
3175 GOTO 3210
3180 IF I1>3 THEN 3200
3185 R1=Y(5,P(5)-1)*O/K1*N1
3190 GOSUB 6500
3195 GOTO 3210
3200 R1=Y(6,P(6)-1)*O/(K2*(U(2)-U(1)))*N2
3205 GOSUB 6500
3210 PRINT VAL$(R1);" ";V4$[Z(I1-1)+1,Z(I1)];" at ";
3215 R1=(X(1,P(1)-1)-U(1))*N
3220 GOSUB 6500
3225 PRINT VAL$(R1);" ";U2$;"." @ PRINT
3230 NEXT I1
3235 FOR I1=2 TO P(1)-1
3240 IF (Y(1,I1)-V(3))/(Y(1,P(1)-1)-V(3))>.1 THEN 3247
3245 NEXT I1
3247 I1=I1-1
3250 PRINT @ PRINT "The time at 10% "
```

```
2730 REM *     1) MAKES SEPARATE PLOTS
2740 REM *        OF 2 OBJECT CURVES,
2750 REM *        PRODUCT CURVE, AND
2760 REM *        TIME INTEGRAL
2770 REM *        CURVE
2780 REM *
2790 REM *
2800 I1=1
2805 GOTO 3380
2810 I1=2
2815 GOTO 3380
2820 I1=3
2825 GOTO 3380
2830 I1=4
2835 GOTO 3380
2840 CLEAR @ GCLEAR
2842 BEEP 200,50
2845 DISP "Do you want a standard 8 x 10"
2850 DISP "grid? (Y/N)"
2855 INPUT G1$
2860 IF G1$="Y" THEN G$="Y" @ U1=10 @ V1=8 @ GOTO 2900
2865 CLEAR @ DISP "Do you want a grid on the plot?"
2870 DISP "(Y/N)"
2875 INPUT G$
2880 DISP @ DISP "How many horizontal divisions?"
2885 INPUT U1
2890 DISP @ DISP "How many vertical divisions?"
2895 INPUT V1
2900 CLEAR @ DISP "How much is each horizontal"
2905 DISP "division? (magnitude,unit)"
2910 DISP "[5 mV is 5, mV.]"
2915 INPUT U2,U2$
2920 DISP @ DISP "How much is each division on"
2925 DISP "the first vertical axis?"
2930 DISP "(magnitude,unit)"
2935 DISP "[5 mV is 5, mV.]"
2940 INPUT V2(1),V4$
2945 DISP @ DISP "How much is each division on"
2950 DISP "the second vertical axis?"
2955 DISP "(magnitude,unit)"
2960 DISP "[5 mV is 5, mV.]"
2965 INPUT V2(2),V5$
2970 Z(0)=0 @ Z(1)=LEN(V4$)
2975 Z(2)=LEN(V5$)+Z(1)
2980 V4$=V4$&V5$
2985 M1=0 @ L1=0 @ J=3
2990 M$=" " @ L$=" " @ J$=" "
2995 K1=IP((V(1)-V(3))^2/A)
3000 IF K1>0 THEN K1=1/K1 @ GOTO 3010
3005 K1=IP(A/(V(1)-V(3))^2)
3010 V2(3)=K1*V2(1)*V2(2)*V1
```

```
1410 IF Y(A1,I1)>=A THEN A=Y(A1,I1)
1420 NEXT I1
1440 FOR I1=1 TO P(1)-1
1450 X(B1,I1)=X(1,I1)
1470 IF I1=1 THEN Y(B1,I1)=Y(A1,I1)*(X(1,I1)-U(3)) @ GOT
O 1490
1480 Y(B1,I1)=Y(A1,I1)*(X(1,I1)-X(1,I1-1))+Y(B1,I1-1)
1485 IF X(1,I1)-X(1,I1-1)>=C THEN C=X(1,I1)-X(1,I1-1)
1490 IF Y(B1,I1)>=B THEN B=Y(B1,I1)
1500 NEXT I1
1510 RETURN
1600 REM *
1610 REM *
1620 REM *  READ SUBROUTINE
1630 REM *     1) READS ARRAY
1640 REM *        (TAPE OR DISK)
1650 REM *
1660 REM *
1670 FOR I2=1 TO P1
1680 FOR I3=1 TO P(I2)-1
1690 K=K+1
1700 READ# 1,K ; X(I2,I3)
1710 READ# 2,K-2 ; Y(I2,I3)
1720 NEXT I3
1730 NEXT I2
1740 RETURN
1800 REM *
1810 REM *
1820 REM *  CLOSE SUBROUTINE
1830 REM *     1) CLOSE FILES
1840 REM *
1850 REM *
1860 ASSIGN# 1 TO *
1870 ASSIGN# 2 TO *
1880 RETURN
1900 REM *
1910 REM *
1920 REM *  MASS STORAGE SUBROUTINE
1930 REM *  1) ESTABLISH MEDIUM
1940 REM *
1950 IF R$="TAPE" THEN 1980
1955 IF R$="DISK01" THEN 1970
1960 MASS STORAGE IS ":D700"
1965 GOTO 1990
1970 MASS STORAGE IS ":D701"
1975 GOTO 1990
1980 MASS STORAGE IS ":T"
1990 RETURN
2700 REM *
2710 REM *
2720 REM *  PLOT SUBROUTINE
```

```
1130 X(4,I1)=X(1,I1)
1135 NEXT I1
1140 FOR I1=1 TO P(2)-1
1145 X(4,I1+P(1)-1)=X(2,I1)
1150 NEXT I1
1155 FOR I1=1 TO P(4)-1
1160 FOR I2=I1 TO P(4)-1
1165 IF X(4,I1)>X(4,I2) THEN R5=X(4,I1) @ X(4,I1)=X(4,I2
) @ X(4,I2)=R5
1170 NEXT I2
1175 NEXT I1
1180 FOR I1=2 TO P(1)-1
1185 FOR I2=I4 TO P(4)-2
1190 I4=I2
1195 IF X(4,I2)>X(1,I1) THEN 1210
1200 Y(4,I2-1)=M(1,I1-1)*X(4,I2)+M(2,I1-1)
1205 NEXT I2
1210 NEXT I1
1215 P(1)=P(4)-2 @ I4=2
1217 FOR I1=1 TO P(1)-1
1219 Y(1,I1)=Y(4,I1)
1221 X(1,I1)=X(4,I1+1)
1223 NEXT I1
1225 FOR I1=2 TO P(2)-1
1230 FOR I2=I4 TO P(4)-2
1235 I4=I2
1240 IF X(4,I2)>X(2,I1) THEN 1255
1245 Y(4,I2-1)=M(3,I1-1)*X(4,I2)+M(4,I1-1)
1250 NEXT I2
1255 NEXT I1
1260 P(2)=P(4)-2 @ P(3)=P(2)
1262 FOR I1=1 TO P(2)-1
1264 Y(2,I1)=Y(4,I1)
1266 X(2,I1)=X(4,I1+1)
1268 NEXT I1
1270 FOR I1=1 TO P(3)-1
1275 X(3,I1)=Y(C2,I1)
1280 Y(3,I1)=Y(C1,I1)
1285 NEXT I1
1290 RETURN
1300 REM *
1310 REM *
1320 REM *  MATH SUBROUTINE
1330 REM *     1) EVALUATE PRODUCT AND
1340 REM *        TIME INTEGRAL FOR CURVES
1350 REM *
1360 REM *
1370 A=0 @ C=0
1380 FOR I1=1 TO P(1)-1
1390 X(A1,I1)=X(1,I1)
1400 Y(A1,I1)=(Y(1,I1)-V(3))*(Y(2,I1)-V(3))
```

```
445 GOSUB 5300
450 A1=5 @ B1=6
490 GOSUB 1000
510 P(5)=P(1) @ P(6)=P(1)
520 GOSUB 1300
525 GOSUB 2840
530 ON KEY# 1,"PLOT V" GOTO 2800
535 ON KEY# 2,"PLOT I" GOTO 2810
540 ON KEY# 3,"PLOT P" GOTO 2820
545 ON KEY# 4,"PLOT U" GOTO 2830
550 ON KEY# 5,"V-I" GOTO 5600
555 ON KEY# 6,"SCALE" GOTO 4400
560 ON KEY# 7,"STOP" GOTO 600
570 CLEAR @ KEY LABEL
575 BEEP 200,50
580 DISP "Press the desired key."
590 GOTO 590
600 DISP "Are you finished with " @ DISP "this operation
?  (Y/N)"
610 INPUT A$
620 IF A$#"Y" THEN 530
710 DISP "Do you want to work on"
720 DISP "another set of curves?"
730 DISP "(Y/N)"
740 INPUT A$
750 IF A$="Y" THEN 10
755 CLEAR @ MASS STORAGE IS ":D700"
760 CHAIN "SMILE"
770 END
1000 REM *
1010 REM *
1020 REM *  INTERPOLATION SUBROUTINE
1030 REM *     1) FIND SLOPES AND INTERCEPTS
1040 REM *     2) EVALUATE SLOW GRAPH
1050 REM *        FOR RAPID GRAPH POINTS
1060 REM *
1070 REM *
1080 FOR I1=1 TO P(1)-2
1082 IF X(1,I1+1)-X(1,I1)=0 THEN M(1,I1)=M(1,I1-1) @ GOT
O 1090
1085 M(1,I1)=(Y(1,I1+1)-Y(1,I1))/(X(1,I1+1)-X(1,I1))
1090 M(2,I1)=Y(1,I1)-M(1,I1)*X(1,I1)
1095 NEXT I1
1100 FOR I1=1 TO P(2)-2
1102 IF X(2,I1+1)-X(2,I1)=0 THEN M(3,I1)=M(3,I1-1) @ GOT
O 1110
1105 M(3,I1)=(Y(2,I1+1)-Y(2,I1))/(X(2,I1+1)-X(2,I1))
1110 M(4,I1)=Y(2,I1)-M(3,I1)*X(2,I1)
1115 NEXT I1
1120 I4=2 @ P(4)=P(1)+P(2)-1
1125 FOR I1=1 TO P(1)-1
```

```
10 REM *
20 REM *
30 REM *  MATH PACKAGE
40 REM *     MAIN PROGRAM
50 REM *
60 REM *Copyright:   11/16/83
70 REM * gandalf software, inc.
80 REM * Chuck Graves, wizard
90 REM *
100 REM *
105 SHORT X(6,150),Y(6,150),M(4,150)
110 INTEGER P(10),U(4),V(4),Z(4),Z1(4),J4(4)
115 DIM V0$[30]
120 GOSUB 4500
125 BEEP 200,50
130 DISP "What is the name of the"
140 DISP "x-file?"
150 INPUT X$
160 IF LEN(X$)>10 THEN DISP "Name is too large." @ GOTO
130
180 DISP @ DISP "What is the name of the"
190 DISP "y-file?"
200 INPUT Y$
210 IF LEN(Y$)>10 THEN DISP "Name is too large." @ GOTO
180
220 DISP @ DISP "Where are ";X$;" and ";
230 DISP Y$;" stored?  (TAPE/DISK00/DISK01)"
240 INPUT R$
250 GOSUB 1900
260 ASSIGN# 1 TO X$
270 ASSIGN# 2 TO Y$
280 FOR I1=1 TO 10
290 READ# 1,I1 ; P(I1)
300 IF P(I1)>1 THEN Q1=I1 @ P1=I1
310 NEXT I1 @ K=10
320 FOR I2=1 TO 4
330 READ# 2,2*I2-1 ; U(I2)
340 READ# 2,2*I2 ; V(I2)
350 NEXT I2
360 GOSUB 1600
370 GOSUB 1800
380 CLEAR
385 BEEP 200,50
390 DISP "Please list the two curves you"
400 DISP "wish multiplied.  (Separate the"
410 DISP "curves with a comma and in the" @ DISP "order:
 VOLTAGE,CURRENT.)"
420 INPUT A,B
425 CLEAR
440 DISP "WORKING"
```

APPENDIX B

Program MATHPK

```
6135 DISP @ DISP "Enter forward base current."
6140 INPUT D$@ PRINT D$
6145 PRINT @ PRINT "Reverse base current:"
6150 PRINT @ PRINT "     Nominal - ";
6155 DISP @ DISP "Enter nominal reverse base current."
6160 INPUT D$@ PRINT D$
6170 DISP @ DISP "Enter reverse base current at SB"
6180 INPUT D$@ PRINT "     Actual at SB - ";D$
6190 PRINT @ PRINT "Comments:"
6195 DISP @ DISP "Enter any additional comments."
6200 INPUT D$@ PRINT "     ";D$
6205 PRINT @ PRINT @ PRINT
6210 RETURN
```

```
5760 PRINT @ PRINT "3  LOAD"
5770 PRINT "   Load old curves"
5780 PRINT "   from tape or disk."
5790 PRINT @ PRINT "4  SCALE"
5800 PRINT "   Change scale size"
5810 PRINT "   of plot."
5820 PRINT @ PRINT "5  PLOT"
5830 PRINT "   Make intermediate"
5840 PRINT "   plot of curves."
5841 PRINT @ PRINT "6  DEVICE DATA"
5842 PRINT "   Make printout of"
5843 PRINT "   device data."
5850 PRINT @ PRINT "7-16  Not used."
5860 FOR I1=1 TO 5
5870 PRINT @ PRINT
5880 NEXT I1
5885 CLEAR
5890 RETURN
5900 REM *
5910 REM *
5920 REM *  DEVICE DATA
5930 REM *    SUBROUTINE
5940 REM *
5950 REM *
5960 CLEAR
5965 PRINTER IS 2
5970 PRINT @ PRINT "Manufacturer - ";
5975 DISP "Enter manufacturer."
5980 INPUT D$@ PRINT D$
5990 PRINT @ PRINT "Device type - ";
5995 DISP @ DISP "Enter device type."
6000 INPUT D$@ PRINT D$
6010 PRINT @ PRINT "Mask type or other applicable"
6015 DISP @ DISP "Enter mask type or other"
6020 PRINT "data - ";
6025 DISP "applicable data."
6030 INPUT D$@ PRINT D$
6040 CLEAR
6050 PRINT @ PRINT "Device number - ";
6055 DISP @ DISP "Enter device number."
6060 INPUT D$@ PRINT D$
6070 PRINT @ PRINT "Temperature - ";
6075 DISP @ DISP "Enter temperature (RT or"
6080 DISP "degrees C)."
6090 INPUT D$
6095 PRINT D$;" C"
6100 PRINT @ PRINT "SB type - ";
6105 DISP @ DISP "Enter SB type (N,A,B or C)."
6110 INPUT D$@ PRINT D$
6120 CLEAR
6130 PRINT @ PRINT "Forward base current - ";
```

```
5200 DISP "What name do you want for the" @ DISP "y-coor
dinate file?"
5210 INPUT Y5$
5220 IF LEN(Y5$)>10 THEN DISP "Name is too large." @ GOT
O 5200
5230 RENAME "X"&VAL$(Q) TO X5$
5240 RENAME "Y"&VAL$(Q) TO Y5$
5250 RETURN
5300 REM *
5310 REM *
5320 REM *  INITIALIZATION SUBROUTINE
5330 REM *
5340 REM *
5345 DISP @ DISP "INITIALIZING"
5350 FOR I1=1 TO Q
5360 FOR I2=1 TO 150
5370 X(I1,I2)=0
5380 Y(I1,I2)=0
5390 NEXT I2
5400 NEXT I1
5410 FOR I1=1 TO 4
5420 U(I1)=0
5430 V(I1)=0
5440 NEXT I1
5450 FOR I1=1 TO 10
5460 P(I1)=1
5470 NEXT I1
5480 P1=1 @ N1=0 @ H=1 @ H$="A"
5490 G1=.0213 @ G2=.022
5500 PLOTTER IS 1
5505 CLEAR
5510 RETURN
5600 REM *
5610 REM *
5620 REM *  VISUAL AID SUBROUTINE
5630 REM *     A) PRINT SOFTKEY ASSIGNMENTS.
5640 REM *
5650 REM *
5660 PRINTER IS 2
5670 PRINT "Softkey Assignments"
5680 PRINT @ PRINT
5690 PRINT "1   STOP"
5700 PRINT "    End of curve."
5710 PRINT "    Depress to start"
5720 PRINT "    next curve."
5730 PRINT @ PRINT "2  STORE"
5740 PRINT "    Transfer curves"
5750 PRINT "    to tape or disk."
```

```
4310 REM *
4320 REM *  FUNCTION FNX
4330 REM *
4340 REM *
4350 REM *
4360 DEF FNX(A)
4370 B=H*A
4380 FNX=IP(B+.5)
4390 FN END
4500 REM *
4510 REM *
4520 REM *  CORRECTION SUBROUTINE
4530 REM *    A) CALCULATE CORNERS:   (UL,UR,LL,LR)
4540 REM *    B) CALCULATE CORRECTION FACTORS.
4550 REM *
4560 REM *
4570 V1=SQR((U(3)-U(4))^2+(V(3)-V(4))^2)
4580 U5=ATN((V(4)-V(3))/(U(4)-U(3)))
4590 U(4)=U(3)+IP(V1+.5)
4600 V(4)=V(3)
4610 V1=SQR((U(1)-U(3))^2+(V(1)-V(3))^2)
4620 U(1)=U(3)
4625 V(1)=V(3)+IP(V1+.5)
4630 U(2)=U(4)
4640 V(2)=V(1)
4680 RETURN
4700 REM *
4710 REM *
4720 REM *  SKEW SUBROUTINE
4730 REM *    A) ADJUST ROTATION
4740 REM *
4750 REM *
4760 V1=SQR((U(3)-T(1))^2+(V(3)-T(2))^2)
4765 IF T(1)-U(3)=0 THEN V5=PI/2 @ GOTO 4780
4770 V5=ATN((T(2)-V(3))/(T(1)-U(3)))
4780 IF V5<0 AND T(2)-V(3)>0 THEN V5=V5+PI
4790 T(1)=U(3)+IP(V1*COS(V5-U5)+.5)
4800 T(2)=V(3)+IP(V1*SIN(V5-U5)+.5)
4810 RETURN
5100 REM *
5110 REM *
5120 REM *  RENAME SUBROUTINE
5130 REM *    A) REGISTERS ARE USER NAMED.
5140 REM *
5150 REM *
5160 CLEAR
5170 DISP "What name do you want for the" @ DISP "x-coor
dinate file?"
5180 INPUT X5$
5190 IF LEN(X5$)>10 THEN DISP "Name is too large." @ GOT
O 5170
```

```
3730 DRAW FNX(X(I1,I2)),FNX(Y(I1,I2))
3740 NEXT I2
3750 NEXT I1
3752 MOVE 0,V(3)
3753 DRAW 12032,V(3)
3755 WAIT 4000
3760 RETURN
3770 REM *
3780 REM *
3790 REM *   6-16) Not used
3800 REM *
3810 REM *
3820 CLEAR
3830 DISP @ DISP "This softkey performs no function."
3840 DISP @ DISP "Please try another."
3850 N1=N1+1
3860 IF N1<4 THEN GOTO 1900
3865 PLOTTER IS 1
3870 CSIZE 21 @ GCLEAR
3880 SCALE 0,10,0,10
3890 MOVE 1,5
3900 LABEL "HANDS"
3910 MOVE 2,0
3920 LABEL "OFF"
3930 WAIT 2000 @ GCLEAR
3940 RETURN
4000 REM *
4010 REM *
4020 REM *  READ SUBROUTINE
4030 REM *     1) READS ARRAY
4040 REM *        (TAPE OR DISK)
4050 REM *
4060 REM *
4070 FOR I2=1 TO P1
4080 FOR I3=1 TO P(I2)-1
4090 M=M+1
4100 READ# 1,M ; X(I2,I3)
4110 READ# 2,M-2 ; Y(I2,I3)
4120 NEXT I3
4130 NEXT I2
4140 RETURN
4200 REM *
4210 REM *
4220 REM *  CLOSE SUBROUTINE
4230 REM *     1) CLOSE FILES
4240 REM *
4250 REM *
4260 ASSIGN# 1 TO *
4270 ASSIGN# 2 TO *
4260 RETURN
4300 REM *
```

```
3320 REM *    3) LOAD
3330 REM *
3340 REM *
3350 CLEAR
3360 DISP "What is the name of the x-file?"
3370 INPUT X$
3375 IF LEN(X$)>10 THEN DISP "Name is too large." @ GOTO
 3360
3380 DISP @ DISP "What is the name of the y-file?"
3390 INPUT Y$
3395 IF LEN(Y$)>10 THEN DISP "Name is too large." @ GOTO
 3380
3400 DISP @ DISP "Where are ";X$;" and ";@ DISP Y$;" sto
red? (TAPE/DISK00/DISK01)"
3410 INPUT R$
3420 GOSUB 2700
3430 ASSIGN# 1 TO X$
3440 ASSIGN# 2 TO Y$
3450 FOR I1=1 TO 10
3460 READ# 1,I1 ; P(I1)
3470 IF P(I1)>1 THEN Q=I1 @ P1=I1
3480 NEXT I1 @ M=10
3482 FOR I2=1 TO 4
3484 READ# 2,2*I2-1 ; U(I2)
3486 READ# 2,2*I2 ; V(I2)
3488 NEXT I2
3500 GOSUB 4000
3505 GOSUB 4200
3510 GOTO 390
3520 REM *
3530 REM *
3540 REM *    4) SCALE
3550 REM *
3560 REM *
3570 CLEAR
3580 DISP "Enter the scale factor for" @ DISP "plotting.
 (less than 4.0)"
3590 INPUT H
3600 REM *
3610 REM *
3620 REM *    5) PLOT
3630 REM *
3640 REM *
3650 CLEAR
3660 DISP "Do you want a plot or display" @ DISP "of the
 data so far?" @ DISP "(DISP/PLOT)"
3670 INPUT H$@ CLEAR @ GCLEAR
3690 SCALE 0,12032,0,9012
3700 FOR I1=1 TO P1
3710 MOVE FNX(X(I1,1)),FNX(Y(I1,1))
3720 FOR I2=2 TO P(I1)-1
```

```
3420 AXES U2,V2(I1),0,0,1,1,3
3425 GOTO 3435
3430 GRID U2,V2(I1),0,0,1,1,1
3435 FOR I2=1 TO U1
3440 MOVE I2*U2,-(V2(I1)/10)
3445 LABEL VAL$(I2*U2)
3450 NEXT I2
3455 LORG 8
3460 FOR I3=1 TO V1
3465 MOVE -(U2/8),I3*V2(I1)
3470 LABEL VAL$(IP(I3*V2(I1)+.5))
3475 NEXT I3
3480 LORG 6 @ CSIZE (H*(U(2)-U(1))/8831*100+10)/16,.5
3485 MOVE .5*U1*U2,-(V1*V2(I1)/10)
3490 LABEL U$;" (";U2$;")"
3495 DEG @ LDIR 90 @ LORG 4
3500 MOVE -(U1*U2/10),.5*V1*V2(I1)
3505 LABEL VO$[Z1(I1-1)+1,Z1(I1)];" (";V4$[Z(I1-1)+1,Z(I
1)];")"
3510 RAD @ LDIR 0
3515 O=V1*V2(I1)/(V(1)-V(3))^(1+IP((I1-1)/2))
3520 IF I1>2 THEN 3550
3525 MOVE (X(I1,1)-U(1))*N,(Y(I1,1)-V(3))*O
3530 FOR I2=2 TO P(I1)-1
3535 DRAW (X(I1,I2)-U(1))*N,(Y(I1,I2)-V(3))*O
3540 NEXT I2
3545 GOTO 3600
3550 IF I1>3 THEN 3580
3555 MOVE (X(5,1)-U(1))*N,Y(5,1)*O/K1*N1
3560 FOR I2=2 TO P(5)-1
3565 DRAW (X(5,I2)-U(1))*N,Y(5,I2)*O/K1*N1
3570 NEXT I2
3575 GOTO 3600
3580 MOVE (X(6,1)-U(1))*N,Y(6,1)*O/(K2*(U(2)-U(1)))*N2
3585 FOR I2=2 TO P(6)-1
3590 DRAW (X(6,I2)-U(1))*N,Y(6,I2)*O/(K2*(U(2)-U(1)))*N2

3595 NEXT I2
3600 CLEAR @ DISP "How many lines does the"
3605 DISP "main title have?"
3610 BEEP 200,50
3615 INPUT T1
3620 LORG 4
3625 FOR I2=1 TO T1
3630 DISP @ DISP "What is line ";VAL$(I2);"?"
3635 INPUT T$
3640 DISP @ DISP "Where do you want line ";VAL$(I2)
3645 DISP "printed?"
3650 DISP "(Give y-coordinate from the"
3655 DISP "graph.)"
```

```
3660 INPUT T2
3665 MOVE .5*U1*U2,T2
3670 LABEL T$
3675 NEXT I2
3680 GOTO 530
3800 REM *
3810 REM *
3820 REM *  STRING SUBROUTINE
3830 REM *     1) CALCULATE UNITS FOR
3840 REM *        PRODUCT AND INTEGRAL
3850 REM *        CURVES
3860 REM *
3870 REM *
3875 IF LEN(J$)<2 THEN 3890
3885 L$=L$&J$[J4(2),J4(3)-1]
3890 IF Z(1)<=1 THEN 3910
3900 L$=L$&V4$[1,Z(1)-1]
3910 IF Z(2)-Z(1)<=1 THEN 3930
3920 L$=L$&V4$[Z(1)+1,Z(2)-1]
3930 IF LEN(L$)<=2 THEN 4060
3940 FOR I1=1 TO LEN(L$)
3943 IF L$[I1,I1]="M" THEN L1=L1+6
3946 IF L$[I1,I1]="k" THEN L1=L1+3
3950 IF L$[I1,I1]="m" THEN L1=L1-3
3955 IF L$[I1,I1]="u" THEN L1=L1-6
3960 IF L$[I1,I1]="n" THEN L1=L1-9
3970 IF L$[I1,I1]="p" THEN L1=L1-12
3980 NEXT I1
3981 IF L1=12 THEN L$=" T"
3982 IF L1=9 THEN L$=" G"
3983 IF L1=6 THEN L$=" M"
3984 IF L1=3 THEN L$=" k"
3985 IF L1=0 THEN L$=" "
3986 IF L1=-3 THEN L$=" m"
3990 IF L1=-6 THEN L$=" u"
4000 IF L1=-9 THEN L$=" n"
4010 IF L1=-12 THEN L$=" p"
4020 IF L1=-15 THEN L$=" f"
4030 IF L1=-18 THEN L$=" c"
4040 IF L1=-21 THEN L$=" y"
4050 IF L1=-24 THEN L$=" z"
4060 L$=L$&"W"
4065 IF LEN(J$)<2 THEN 4075
4070 M$=M$&J$[J4(3),J4(4)-1]
4075 IF Z(1)<=1 THEN 4085
4080 M$=M$&V4$[1,Z(1)-1]
4085 IF Z(2)-Z(1)<=1 THEN 4092
4090 M$=M$&V4$[Z(1)+1,Z(2)-1]
4092 IF LEN(U2$)<=1 THEN 4100
4095 M$=M$&U2$[1,LEN(U2$)-1]
```

```
4100 IF LEN(M$)<=2 THEN 4310
4110 FOR I1=1 TO LEN(M$)
4120 IF M$[I1,I1]="M" THEN M1=M1+6
4130 IF M$[I1,I1]="k" THEN M1=M1+3
4140 IF M$[I1,I1]="m" THEN M1=M1-3
4145 IF M$[I1,I1]="u" THEN M1=M1-6
4150 IF M$[I1,I1]="n" THEN M1=M1-9
4160 IF M$[I1,I1]="p" THEN M1=M1-12
4170 NEXT I1
4180 IF M1=12 THEN M$=" T"
4190 IF M1=9 THEN M$=" G"
4200 IF M1=6 THEN M$=" M"
4210 IF M1=3 THEN M$=" k"
4220 IF M1=0 THEN M$=" "
4230 IF M1=-3 THEN M$=" m"
4240 IF M1=-6 THEN M$=" u"
4250 IF M1=-9 THEN M$=" n"
4260 IF M1=-12 THEN M$=" p"
4270 IF M1=-15 THEN M$=" f"
4280 IF M1=-18 THEN M$=" a"
4290 IF M1=-21 THEN M$=" y"
4300 IF M1=-24 THEN M$=" z"
4310 M$=M$&"J"
4320 M$=M$[2,LEN(M$)]
4330 L$=L$[2,LEN(L$)]
4340 Z(3)=LEN(L$)+Z(2)
4350 Z(4)=LEN(M$)+Z(3)
4360 V4$=V4$&L$&M$
4370 RETURN
4400 REM *
4410 REM *
4420 REM *  SCALE SUBROUTINE
4430 REM *
4440 REM *
4450 CLEAR
4460 DISP "Enter the scale factor for"
4470 DISP "plotting.  (less than 4.0)"
4480 INPUT H
4485 H=2*H
4490 GOTO 530
4500 REM *
4510 REM *
4520 REM *  INITIALIZATION SUBROUTINE
4530 REM *
4540 REM *
4550 CLEAR @ GCLEAR
4560 DISP @ DISP "INITIALIZING"
4565 FOR I1=1 TO 2
4570 FOR I2=1 TO 150
4575 X(I1,I2)=0
4580 Y(I1,I2)=0
```

```
4585 NEXT I2
4590 NEXT I1
4630 FOR I1=1 TO 4
4635 Z(I1)=0
4640 U(I1)=0
4650 V(I1)=0
4655 J4(I1)=2
4660 NEXT I1
4670 FOR I1=1 TO 2
4680 P(I1)=1
4690 NEXT I1
4700 P1=1 @ H=1
4710 PLOTTER IS 705
4725 FOR I1=3 TO 6
4730 FOR I2=1 TO 150
4735 M(1,I2)=0
4740 X(I1,I2)=0
4745 M(2,I2)=0
4750 Y(I1,I2)=0
4755 NEXT I2
4760 NEXT I1
4765 FOR I1=3 TO 10
4770 P(I1)=1
4775 NEXT I1
4780 CLEAR @ H=2
4790 RETURN
5000 REM *
5010 REM *
5020 REM *  FUNCTION FNA
5030 REM *     1) MAKE THE LABELS AN
5040 REM *        INCREMENT OF 10
5050 REM *     2) ADJUST LABEL TO CORRECT
5060 REM *        ENGINEERING UNIT
5070 REM *
5080 REM *
5090 DEF FNA(B)
5100 J3=0
5110 FOR J1=1 TO 5
5120 B=B/1000
5130 IF B<1 THEN 5155
5140 J4(J)=J4(J)+1
5150 NEXT J1
5155 J5=J4(J)-2
5157 IF J5<1 THEN 5185
5160 FOR J2=1 TO J5
5170 J$=J$&"k"
5180 NEXT J2
5185 B=B*1000 @ C=B
5190 FOR J1=1 TO 3
5200 B=B/10
5210 IF B<1 THEN 5240
```

```
5220 J3=J3+1
5230 NEXT J1
5240 B=(IP(B*10)+1)*10^J3
5245 J=J+1
5250 FNA=B
5260 FN END
5300 REM *
5310 REM *
5320 REM *  TRANSFER SUBROUTINE
5330 REM *     1) TAKE IN TWO CURVES
5340 REM *        AND MOVE THEM TO
5350 REM *        REGISTERS 1 & 2
5360 REM *
5370 REM *
5380 IF A>B THEN F=B @ B=A @ A=F @ C1=1 @ C2=2 @ GOTO 53
90
5385 C1=2 @ C2=1
5390 IF A=1 THEN 5466
5420 P(1)=P(A)
5430 FOR I1=1 TO P(1)-1
5440 X(1,I1)=X(A,I1)
5450 Y(1,I1)=Y(A,I1)
5460 NEXT I1
5466 IF B=2 THEN 5515
5470 P(2)=P(B)
5480 FOR I1=1 TO P(2)
5490 X(2,I1)=X(B,I1)
5500 Y(2,I1)=Y(B,I1)
5510 NEXT I1
5515 GOSUB 6200
5520 GOSUB 4725
5530 A=1 @ B=2
5540 RETURN
5600 REM *
5610 REM *
5620 REM *  PLOT SUPPLEMENT
5630 REM *     1) MAKES V-I CURVE
5640 REM *
5650 REM *
5660 CLEAR
5670 DISP "Load the printer and press" @ DISP "CONTINUE.
"
5680 PAUSE
5685 LORG 6 @ CSIZE (H*(U(2)-U(1))/8831*50+10)/19,.3
5690 LOCATE 10,H*(V(1)-V(3))/8831*50+10,10,H*(V(1)-V(3))
/8831*50+10
5700 FRAME
5710 SCALE 0,V1*V2(C2),0,V1*V2(C1)
5720 IF G$="Y" THEN 5750
5730 AXES V2(C2),V2(C1),0,0,1,1,3
```

```
5740 GOTO 5760
5750 GRID V2(C2),V2(C1),0,0,1,1,1
5760 FOR I2=1 TO V1
5770 MOVE I2*V2(C2),-(V2(C1)/10)
5780 LABEL VAL$(I2*V2(C2))
5790 NEXT I2
5800 LORG 8
5810 FOR I3=1 TO V1
5820 MOVE -(V2(C2)/8),I3*V2(C1)
5830 LABEL VAL$(IP(I3*V2(C1)+.5))
5840 NEXT I3
5850 LORG 6 @ CSIZE (H*(V(1)-V(3))/8831*100+10)/16,.5
5860 MOVE .5*V1*V2(C2),-(V1*V2(C1)/10)
5870 LABEL V0$[Z1(C2-1)+1,Z1(C2)];" (";V4$[Z(C2-1)+1,Z(C
2)];")"
5880 DEG @ LDIR 90 @ LORG 4
5890 MOVE -(V1*V2(C2)/10),.5*V1*V2(C1)
5900 LABEL V0$[Z1(C1-1)+1,Z1(C1)];" (";V4$[Z(C1-1)+1,Z(C
1)];")"
5910 RAD @ LDIR 0
5920 N=V1*V2(C2)/(V(1)-V(3))
5930 O=V1*V2(C1)/(V(1)-V(3))
5940 MOVE (X(3,1)-V(3))*N,(Y(3,1)-V(3))*O
5950 FOR I2=2 TO P(3)-1
5960 DRAW (X(3,I2)-V(3))*N,(Y(3,I2)-V(3))*O
5970 NEXT I2
5980 CLEAR @ DISP "How many lines does the main"
5990 DISP "title have?"
6000 BEEP 200,50
6010 INPUT T1
6020 LORG 4
6030 FOR I2=1 TO T1
6040 DISP @ DISP "What is line";I2;"?" @ INPUT T$
6050 DISP @ DISP "Where do you wnt line";I1 @ DISP "prin
ted?"
6060 DISP "(Give y-coordinate from the" @ DISP "graph.)"

6070 INPUT T2
6080 MOVE .5*V1*V2(C2),T2
6090 LABEL T$
6100 NEXT I2
6110 GOTO 530
6200 REM *
6210 REM *
6220 REM *  SUPPLEMENTARY TRANSFER
6230 REM *       SUBROUTINE
6240 REM *
6250 REM *
6260 IF X(1,1)>X(2,1) THEN R1=2 @ R2=X(1,1) @ GOTO 6280
6270 R1=1 @ R2=X(2,1)
```

END

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